REPORT OF SURVEY CONDUCTED AT

APPLIED RESEARCH LABORATORY,
PENNSYLVANIA STATE UNIVERSITY
STATE COLLEGE, PA

MARCH 1999

Best Manufacturing Practices

1998 Award Winner

INNOVATIONS IN AMERICAN GOVERNMENT

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Foreword

This report was produced by the Office of Naval Research's Best Manufacturing Practices (BMP) program, a unique industry and government cooperative technology transfer effort that improves the competitiveness of America's industrial base both here and abroad. Our main goal at BMP is to increase the quality, reliability, and maintainability of goods produced by American firms. The primary objective toward this goal is simple: to identify best practices, document them, and then encourage industry and government to share information about them.

The BMP program set out in 1985 to help businesses by identifying, researching, and promoting exceptional manufacturing practices, methods, and procedures in design, test, production, facilities, logistics, and management – all areas which are highlighted in the Department of Defense's 4245.7-M, *Transition from Development to Production* manual. By fostering the sharing of information across industry lines, BMP has become a resource in helping companies identify their weak areas and examine how other companies have improved similar situations. This sharing of ideas allows companies to learn from others' attempts and to avoid costly and time-consuming duplication.

BMP identifies and documents best practices by conducting in-depth, voluntary surveys such as this one at the Applied Research Laboratory at the Pennsylvania State University (ARL Penn State), State College, Pennsylvania conducted during the week of March 8, 1999. Teams of BMP experts work hand-in-hand on-site with the company to examine existing practices, uncover best practices, and identify areas for even better practices.

The final survey report, which details the findings, is distributed electronically and in hard copy to thousands of representatives from industry, government, and academia throughout the U.S. and Canada – *so the knowledge can be shared*. BMP also distributes this information through several interactive services which include CD-ROMs, BMPnet, and a World Wide Web Home Page located on the Internet at http://www.bmpcoe.org. The actual exchange of detailed data is between companies at their discretion.

By solving challenges for the U.S. Navy, ARL Penn State achieves innovation and practicality in technology-based research. Through its relationship with Penn State, the Laboratory accesses a vast array of multidisciplinary resources and expertise. Together, these avenues foster a collaborative effort that matches real-world problems with advanced research capabilities. Among the best examples were ARL Penn State's accomplishments in overspray capture system; design infrastructure; laser induced breakdown spectroscopy; problem solving focus; laser-liquid-solid interaction technique; and technology transfer and deployment.

The Best Manufacturing Practices program is committed to strengthening the U.S. industrial base. Survey findings in reports such as this one on ARL Penn State expand BMP's contribution toward its goal of a stronger, more competitive, globally-minded, and environmentally-conscious American industrial program.

I encourage your participation and use of this unique resource.

Ernie Renner
Director, Best Manufacturing Practices

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Section 1

Report Summary

Background

The Applied Research Laboratory at the Pennsylvania State University (ARL Penn State) was established in 1945 to advance the U.S. Navy's technology base through research and development (R&D). Today, ARL Penn State serves as a center of research excellence in undersea science and technology. To fulfill this mission, the Laboratory conducts basic and applied research, exploratory activities, and advanced development in support of the Navy's undersea technology base and related mission areas; contributes to the educational objectives, research goals, and scholarly reputation of the University; and promotes the transfer of advanced technology, technology extension, and training to the government and industrial sectors.

Located in the central Pennsylvania community of State College (affectionately known as Happy Valley), this Navy-sponsored facility is supported by more than 900 faculty, staff, and students. ARL Penn State devotes approximately 200,000 square feet to on-site engineering and testing facilities, maintains several remote test sites, and has offices in Keyport, Washington; Warminister, Pennsylvania; and Washington, D.C. Total funding for the facility was $70 million in 1998. ARL Penn State represents one of four Navy academic research centers in the country, and is the largest interdisciplinary center at Penn State. Among the best practices documented were ARL Penn State's overspray capture system; design infrastructure; laser induced breakdown spectroscopy; problem solving focus; laser-liquid-solid interaction technique; and technology transfer and deployment.

In accordance with the Department of Defense and congressional mandates, ARL Penn State's charter promotes technology transfer for economic competitiveness. The Laboratory shares its expertise, capabilities, and research with the Navy through its commands, laboratories, and contractors as well as with other federal agencies, state and regional governments, and industry. Transferring technologies from federally-funded R&D to the Nation's commercial sector augments the Navy's and industry's R&D efforts; adds value to existing and emerging technologies; and enhances ARL Penn State's research and academic efforts.

By solving challenges for the Navy, ARL Penn State achieves innovation and practicality in technology-based research. Through its relationship with Penn State, the Laboratory accesses a vast array of multidisciplinary resources and expertise. Together, these avenues foster a collaborative effort that matches real-world problems with advanced research capabilities. This arrangement also proves to be a competitive strength to ARL Penn State in winning project awards and in attracting support/resources for its many successful programs. The BMP survey team considers the following practices to be among the best in industry and government.

Best Practices

The following best practices were documented at ARL Penn State:

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Composite Structures Prototyping	**7**
ARL Penn State is a leader in the development of composite materials technology for structural applications. Using a concurrent engineering approach, the laboratory developed a rapid prototyping capability for sub-scale and full-scale composite structures. This approach requires a close and continuous interaction between all key technology disciplines (e.g., structures, acoustics, materials, manufacturing, quality control) to maintain a balance between structural integrity, performance, producibility, and cost.	
Design Infrastructure	**7**
ARL Penn State developed and implemented a Simulation Based Design system which rapidly searches the design domain by integrating software tools for design creation; cost and performance estimation; and storage. This system uses virtual prototyping to rapidly evaluate design/decision alternatives for cost, mission effectiveness, reliability, maintainability, and manufacturability.	
Knowledge Based Engineering	**8**
ARL Penn State implemented a generative technology or Knowledge Based Engineering approach to rapidly develop virtual prototypes. This approach captures discipline rules; integrates engineering computer languages with geometric modelers; and generates various outputs such as computer aided design models, dimensional drawings, analysis reports, and manufacturing data.	

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Nanoparticle Fabrication of Tools — 8

ARL Penn State developed a nanograined material for the manufacture and coating of cutting tools used for machining/milling titanium. By processing and applying nanophase powders to these tools, the laboratory increased tool life by two-fold.

Simulation Based Design Cost Estimating — 9

ARL Penn State developed and implemented a Simulation Based Design Cost Estimating system to perform rapid financial evaluations of virtual prototypes. The system uses commercial-off-the-shelf cost estimating software to directly obtain data from the design server and generate a product cost estimate during the early design phase of the acquisition process. Hardware, software development, procurement and support costs are estimated parametrically.

Thermolastically Tailored Cutting Tools — 9

Cutting tools must have high hardness and stiffness to resist deformation under high cutting forces; be high-wear resistant to maintain sharp cutting edges; and permit high machining accuracy over extended periods of time. ARL Penn State has developed laminated ceramic composite cutting tools, which demonstrate improvements in strength, toughness, and thermal shock resistance compared to conventional, non-laminated ceramic composites.

Condition Based Maintenance — 10

ARL Penn State instituted a systems approach for Condition Based Maintenance by using a hierarchical architecture for developing and implementing health assessment systems. This hierarchy represents the decomposition of a system including the highest level from which the demand originates, the impact of the failure, and the lowest level from which all failures originate.

Gear and Gear Materials Testing — 10

The expense of operating a gear test facility is deterring many aircraft manufacturers from setting up in-house test capabilities. However, ARL Penn State has obtained the necessary equipment to provide gear and gear materials testing services to the aircraft industry. The laboratory offers power circulating gear tests for surface durability and wear; low speed bending; scuffing; single-tooth bending fatigue; and rolling/sliding contact fatigue.

Phase Shift Optical Triangulation — 11

The key to drivetrain performance, in terms of noise and wear, is gear geometry accuracy. ARL Penn State developed a non-contact, high-speed precision gear measurement system with sensitivity equal to coordinate measuring machines, but with much higher speed and spatial data density. The Phase Shifting Triangulation system measures a gear surface and compares it to a master gear profile. To date, a surface profile accuracy of one micron, and a speed of one tooth per second have been demonstrated.

Portable Phase-Stepping Digital Shearography — 11

ARL Penn State developed the Portable Phase-Stepping Digital Shearography system which can perform full-field, non-contact inspection of suspected damage to aircraft structure in situ. The system can detect surface deformations with a sensitivity of 1/100th of an optical wavelength (five nanometers), which greatly increases the flaw detection capability. The portability of the system allows the device to be used in nearly any environment including shipboard.

Abrasive Flow Machining — 12

The Navy approached ARL Penn State to evaluate Abrasive Flow Machining as an alternative way to prepare turbine blades for re-coating. As a result, the laboratory developed analytical techniques to optimize this method's setup for removing thin coatings (two to four mils). Abrasive Flow Machining removes very small amounts of surface material by forcing a highly viscous fluid or carrier, containing an abrasive, back and forth across the surface. The process is several orders of magnitude faster than current techniques of grinding, sandblasting, or chemical etching and generates no environmentally hazardous waste stream.

Alternative Lubricants and Environmental Implications — 13

At the request of the Navy, ARL Penn State performed a study on the use of alternate lubricants for MS 2190 TEP. A new formulation, SHC 2190, was developed which is completely compatible with MS 2190 for ease and efficiency of substitution. The study also showed that SHC 2190 had superior performance and biodegradability.

Information

The following information items were documented at ARL Penn State:

Item — **Page**

hull components through the use of numerical modeling. The Laser Assisted Forming process relies on controlled localized heat to create stress states that result in semi-predictable distortion. This process primarily involves angular distortion with the amount of distortion related to the power of the laser; the processing speed; and the thickness and composition of the material being formed.

Laser Cutting and Welding of Lightweight Structures — **29**

ARL Penn State is a leader in developing laser technology processes for cutting, welding, and fabricating lightweight structures. Components formerly made from castings are now being examined as candidates for laser technology process fabricating. In most cases, this technology reduces weight without sacrificing the functionality or design requirements of the finished product.

Laser Free Forming of Structures — **29**

Over the years, ARL Penn State has led the way in laser free forming technology and continues to apply this process on different shapes by using various alloys. Sponsored by the Office of Naval Research, ARL Penn State has been developing laser processing and equipment to refine laser free forming technology. The goal is to establish faster deposition rates than those currently achieved. The work at ARL Penn State has been devoted primarily to titanium free forming of large (up to one meter dimension) structures.

Laser-Liquid-Solid Interaction Technique — **30**

ARL Penn State developed a novel process for synthesizing nanoparticles and nanotubes/nanorods. The process utilizes a Laser-Liquid-Solid Interaction which produces uniformly small particles from the precipitation of a solution. Applications are possible in many disciplines such as biotechnology, electronics, and structures.

Overspray Treatment System — **31**

ARL Penn State designed a system to treat emissions from ship hull coating maintenance operations. This treatment system uses a standard wet filter as well as an adsorption bio-filter to reduce emissions to compliance levels.

Treating Bilgewater Using Critical/Super Critical Carbon Dioxide — **31**

ARL Penn State is working with the Navy to derive a better way of treating contaminated bilgewater in deployed Naval ships. This investigation is evaluating the use of Critical/Super Critical Carbon Dioxide and is using a laboratory-scale system to extract contaminants from simulated bilgewater. The process is highly effective and introduces no additional contaminants to the waste stream.

Technology Transfer of Condition Based Maintenance Technology — **31**

ARL Penn State is among the leaders in the Condition Based Maintenance technology community that notes the importance of transferring Operational Equipment Asset Management technology from the laboratory to the workplace. Taking the lead on this effort, ARL Penn State established the Operational Equipment Asset Management Consortium made up of government and industry representatives who are striving to channel this technology through a proposed effort.

University Relationship — **32**

ARL is an integral part of the Pennsylvania State University, which gives the laboratory an extended capability to manage and perform interdisciplinary research. Through its relationship, ARL Penn State has access to a vast array of resources and expertise which it draws on to support clients. This arrangement also proves to be a competitive strength to ARL Penn State in winning project awards and in attracting support/resources for its many successful programs.

Point of Contact

For further information on items in this report, please contact:

Mr. Lewis Watt
Applied Research Laboratory
The Pennsylvania State University
North Atherton Street
P.O. Box 30
State College, PA 16804
Phone: (814) 863-3880
Fax: (814) 863-1183
E-mail: lcw2@psu.edu
Web: http://www.arl.psu.edu

Section 2

Best Practices

Design

Composite Structures Prototyping

The Applied Research Laboratory at the Pennsylvania State University (ARL Penn State) is a leader in the development of composite materials technology for structural applications. To support this effort, ARL Penn State relies on experienced technical staff; in-house design/analysis, fabrication, and testing facilities; and an extensive network of proven subcontractors. Using a concurrent engineering approach, the laboratory developed a rapid prototyping capability for sub-scale and full-scale composite structures. This approach requires a close and continuous interaction between all key technology disciplines (e.g., structures, acoustics, materials, manufacturing, quality control) to maintain a balance between structural integrity, performance, producibility, and cost.

By applying lessons learned from previous and ongoing programs, ARL Penn State optimizes its composite structure prototyping processes for metal and advanced material components. The laboratory also employs proven fabrication processes; bases its design on customer-accepted criteria; and integrates conservative design evaluation techniques and high safety factors into the prototypes. The effectiveness of ARL Penn State's rapid prototyping capabilities has been successfully demonstrated through various U.S. Navy and industrial programs:

- Full-scale Hydrodynamics Control Component — ARL Penn State designed and delivered this prototype to the Navy within nine months. The prototype features a 50% weight savings and design robustness via Finite Element Analysis design tools.
- Rotating Biological Reactor — ARL Penn State designed and built this prototype for the wastewater industry within eight months. The all-composite design meets performance requirements and cost objectives. This project also demonstrates customer and component supplier involvement throughout the program, and helped establish an industrial supplier base for production.

ARL Penn State attributes the concurrent engineering approach as the key to its Composite Structures Prototyping program. Major projects typically go from design to prototype in less than one year. This approach successfully blends the key technology disciplines to meet the project's objectives.

Design Infrastructure

ARL Penn State developed and implemented a Simulation Based Design (SBD) system which rapidly searches the design domain by integrating software tools for design creation; cost and performance estimation; and object-oriented storage. This system uses virtual prototyping to rapidly evaluate design/decision alternatives for cost, mission effectiveness, reliability, maintainability, and manufacturability. Prior to this development, no tools existed at ARL Penn State which could integrate design, analysis, performance, and cost applications into a single package. The SBD system is an automated design process (Figure 2-1) which captures rules for system and subsystem technologies; connects these legacy applications over a distributed, heterogeneous environment; and helps engineers make decisions early in the acquisition process.

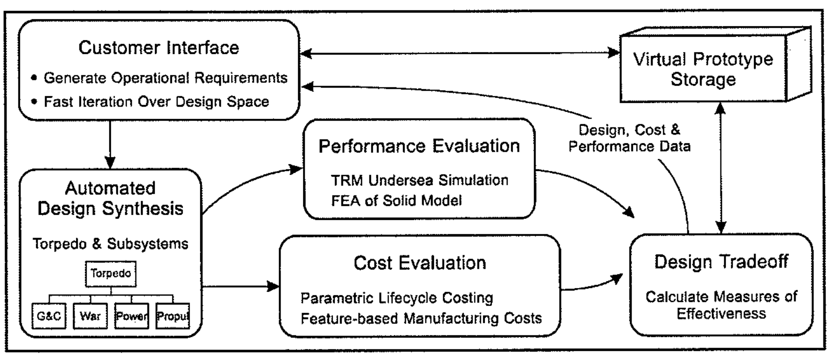


Figure 2-1. Simulation Based Design Flowchart

SBD interconnects knowledge based engineering tools, undersea simulations, computer aided design (CAD), commercial-off-the-shelf (COTS) cost estimating tools, geography applications, customized FORTRAN, C, C++, Visual Basic, JAVA, and object databases. The interoperational environment is based on the Common Object Request Broker Architecture (CORBA), which is used as middleware for communicating between languages, operating systems, and computers. SBD operates on various platforms including Windows 95 and NT; UNIX; and DEC Alpha VMS. The resulting virtual prototype uses geometry to show the relative sizing and placement of components; and data to drive the undersea simulations and parametric cost estimations. The infrastructure formalizes a natural dialog among agents. The information model defines the core of the SBD system by defining product and design variables such as vehicle length, diameter, speed, depth, propulsion power, weight, and endurance. From this model, a database is generated along with the CORBA interfaces to the cost agents, performance agents, and design servers. Custom applications are developed as required with design servers capturing the rules that relate function and constraints to form. The design server checks the input against the information model and then against the constraint map. A constraint map describes the possible combinations of inputs and outputs, and ties the information model to the design server. As a result, a complete model is generated. Design model data is also fed into the final software application to determine product financial information.

The targeted applications for SBD technology are torpedoes and autonomous undersea vehicles. This process significantly decreases the development time, once a database is populated. The time it takes to perform design, fabrication, performance, and cost trade studies for a lightweight torpedo concept can be reduced from six months to one month. Additional trade studies can be performed within minutes by varying product size, components, and their locations within the product volume, desired performance, or cost output. Typically, these additional trade studies would have taken several months to complete.

SBD provides sufficient information so informed decisions can be made early in the acquisition process for military and commercial systems. With most of the code being autogenerated and 90% of the process automated, this technology offers very rapid response times for new projects, programs, and technologies. SBD provides ARL Penn State with an excellent cost-effective virtual prototyping system that integrates design, analysis, performance, and cost software applications for rapidly evaluating design/decision alternatives.

Knowledge Based Engineering

ARL Penn State implemented a generative technology or Knowledge Based Engineering (KBE) approach to rapidly develop virtual prototypes. This approach captures discipline rules; integrates engineering computer languages with geometric modelers; and generates various outputs such as CAD models, dimensional drawings, analysis reports, and manufacturing data. In the past, these tasks were done manually.

KBE facilitates true concurrent engineering by integrating discipline rules (e.g., structural, thermal, manufacturing, geometric, analysis, maintenance) into one model. This method can produce conceptual to detailed models; generate CAD designs from models and requirements; and quickly make adjustments when specifications change. The process begins with an Information Model, which is defined by entering system inputs, calculating output variables, and establishing subsections. In the modeling of the Long Endurance Low Frequency Acoustic Source, ARL Penn State used frequency, ping time, length, source level, and ping duration as the system inputs, and calculated the output variables as weight, duty cycle, and deployed canister buoyancy. Next, the model was divided into subsections including float, transducer assembly, and power section. These subsections can also be individually analyzed and optimized. The Design Server then generates various detail levels by using the requirements to determine the sizes and topology of the subsections.

ARL Penn State's design servers are implemented with IntelliCAD (ICAD) which runs on a variety of UNIX platforms. This KBE tool also combines an engineer-friendly programming language with a solid modeling kernel, so that the geometric primitives are directly inserted into the language. As a result, the ICAD models capture the product attributes at every level. KBE also offers an arbitration feature for optimization. This capability optimizes a design by varying the internal subsystem configurations and their locations.

Using the KBE approach, ARL Penn State substantially reduced its product cycle time and costs. Product configurations, including subsystems, can now be rapidly changed and analyzed in minutes compared to weeks using manually integrated design changes.

Nanoparticle Fabrication of Tools

Williams International machines the compressor section of the Tomahawk F107 engine from a titanium forging. In 1996, the company approached ARL Penn State about developing a tool which could machine titanium and last two-fold longer than commercially available tools. Due to wear, only a quarter section of the titanium could be processed before tool replacement was necessary. This additional operation proved to be costly and time consuming. To resolve this issue, ARL Penn State developed a nanograined material for the manufacture and coating of cutting tools used for machining/milling titanium.

In developing nanoparticle fabrication of tools, ARL Penn State faced various obstacles such as the difficulty of machining titanium, poor tool life, reaction to tool, inadequate dimensional control, and poor thermal conductivity. Of the eight coating materials considered by ARL Penn State, titanium-aluminum-nitride proved the best. The laboratory is also consolidating nanocrystalline powders via rapid solid-state techniques (e.g., rapid hot pressing, microwave sintering exotherms) rather than the current practice of using liquid-phase sintering.

By processing and applying nanophase powders to cutting tools, ARL Penn State increased tool life by two-fold. This method reduces fabrication costs of F107 compressors by 50% or $480,000 per year. In addition, the increased tool longevity will reduce the number of tool changes and improve adherence to manufacturing tolerances. Other applications for these tools include the machining of F119 engines, Joint Strike Fighter engines, and Advanced Amphibious Assault Vehicle (AAAV) hatch covers.

Simulation Based Design Cost Estimating

ARL Penn State developed and implemented a Simulation Based Design (SBD) Cost Estimating system to perform rapid financial evaluations of virtual prototypes. The system uses COTS cost estimating software (PRICE Enterprise Edition) to directly obtain data from the design server and generate a product cost estimate during the early design phase of the acquisition process. Hardware, software development, procurement and support costs are estimated parametrically. This software also provides sufficient cost, schedule, and reliability information for early concept design stage and bid proposal efforts. By changing the design parameters, the SBD Cost Estimating system can rapidly evaluate cost, schedule, and reliability data for various product configurations. Previously, product estimates involved time consuming, manual processes to develop proposals.

A product cost model template is created within the COTS cost estimating software. Design, production, and deployment data are developed from the SBD design server and fed into the model. Input product parameters include volume, weight, complexity, production start/end dates, quantity, and years of deployment. The custom interface software then reads the input data files and writes output data files. The complexity can be calibrated using similar product historical data to provide more accurate cost, schedule, and reliability output parameters. Output product parameters include total program cost, unit production cost, tooling, test equipment, design, project management, labor, material, production end date, mean time between failures (non MIL-SPEC), and operational readiness.

By using the SBD Cost Estimating system, ARL Penn State can cost effectively evaluate 100 product configurations in an hour, compared to weeks or months for manual preparation. This system rapidly provides an extensive amount of cost, schedule, and reliability product information for the rapid evaluation of design/decision alternatives. Informed decisions can be made early in the proposal and acquisition processes for military and commercial products.

Thermolastically Tailored Cutting Tools

Cutting tools must have high hardness and stiffness to resist deformation under the high cutting forces exerted in machining operations. These tools must also be high-wear resistant to maintain sharp cutting edges and permit high machining accuracy over extended periods of time. ARL Penn State has developed laminated ceramic composite cutting tools, which demonstrate improvements in strength, toughness, and thermal shock resistance compared to conventional, non-laminated ceramic composites.

Using SiC whisker and TiC particulate reinforced ceramic matrix composites, ARL Penn State designed multilayer structures and fabricated cutting tool inserts for evaluation in machining tests. The composites were fabricated using either AlO or SiN as the matrix, with TiC particulate, TiN particulate, or SiC whisker reinforcements. The laboratory modified the classical plate laminate theory to thermolastically tailor the laminate design and optimize residual stress, toughness, and tribological performance.

ARL Penn State's designs are considered hybrid composites by conventional laminate terminology since they use multiple compositions within a single laminate. Some of these designs used pure alumina surface layers to provide chemically inert material on the rake face, while others used TiC and SiC reinforcement alumina on this surface. ARL Penn State chose laminate designs to avoid large tensile stresses within the lamina, and large differences in stresses between lamina to minimize delamination.

The laminated ceramic composite designs exhibit significantly better wear resistances as well as improved mechanical strength and toughness. ARL

Penn State achieved successful designs by minimizing residual core tensile and interlaminar stresses, while maximizing the compressive residual stress on the contact surfaces. These designs also minimized flank wear and chipping.

Test

Condition Based Maintenance

Condition Based Maintenance (CBM) is a philosophy that uses sensors, algorithms, models, and automated reasoning to monitor the operations of machinery and equipment as well as determine appropriate maintenance tasks prior to an impending failure. Reducing life-cycle costs is the incentive for investing in CBM technology, and maintenance is the largest controllable cost in industry today. By understanding the workings of machinery and equipment, companies can control costs through efficient planning and effective maintenance. Sufficient warning of an impending failure provides an opportunity to maximize maintenance repair effectiveness and minimize resources, materials, and downtime. CBM technology also provides significant savings compared to traditional preventive maintenance based on time or run-to-fail maintenance. To be effective, CBM should operate as a system that detects and classifies an incipient failure; predicts the remaining life cycle of equipment; supports the operator's decision for course of action; interfaces with the control system to take action; aids the maintainer in making repairs; and provides feedback to the logistics support and machinery design communities.

ARL Penn State instituted a systems approach for CBM by using a hierarchical architecture for developing and implementing health assessment systems. This hierarchy represents the decomposition of a system from the highest level at which the demand originates, the impact of the failure, down to the lowest level at which all failures originate. The hierarchy consists of six levels: material, element, component, subsystem, system, and plant platform. By decomposing a system, ARL Penn State can apply diagnostic tools and sensors at the appropriate level to efficiently monitor and assess the health of a specific area. Collectively, individual health assessments at any level provide system health at the next higher level.

To support its expanding CBM efforts, ARL Penn State also established four facilities: Mechanical Diagnostics Test Bed (MDTB); Ball and V-Ring Test Stand; Lubrication Test Loop; and Systems Integration and Technology Transfer Facility. These facilities provide ARL Penn State with unique capabilities to advance the state of diagnostics and prognostics through the development, evaluation, and application of advanced sensing, reasoning, and modeling techniques. Of particular importance is the MDTB, which provides transitional failure data sets to characterize a fault.

ARL Penn State recognizes the importance of CBM issues to its customers. Since 1994, the laboratory established itself as a leader in CBM mechanical systems, and continues to add to its portfolio of projects won through research contracts and grants. These projects cover various CBM issues from materials to decision support.

Gear and Gear Materials Testing

The expense of operating a gear test facility is deterring many aircraft manufacturers from setting up in-house test capabilities. However, ARL Penn State has obtained the necessary equipment to provide gear and gear materials testing services to the aircraft industry. The laboratory offers power circulating gear tests for:

- Surface Durability (pitting) and Wear — The test strategy is to find loads that have an average life-to-failure durability of three- to six-million cycles for high loads and 12- to 15-million cycles for low loads. Six tests are conducted at each of these load levels with the specimen gear running at 900 rpm and the mating gear at 540 rpm. A Weibull statistical analysis of the results establishes the service life of 10%, 50%, and 90% failures with 50% and 90% confidence levels.
- Low Speed Bending — The test strategy is to use a standard 18-tooth specimen gear and a 30-tooth mating gear that have a life-to-bending failure of 250,000 to 500,000 cycles.
- Scuffing — The test strategy is to run the gear set at a low load and speed using a cold/room temperature lubricant for half an hour. Measurements for surface finish occur in 0.5-hour increments after each step, starting with a moderately high load, speed, and lubricant temperature. The load and/or lubricant temperature is increased with each step. The test concludes when surface roughness significantly increases and visible tears (scuff marks) occur at the tip of the driven gear.
- Single-Tooth Bending Fatigue — The test strategy is to identify a load that will cause a failure by using a single-tooth fatigue fixture with cycles of 50,000 to 100,000 and 250,000 to 500,000 cycles. Six tests are performed at each of these load levels.

- Rolling/Sliding Contact Fatigue — The test strategy is to determine the loads by a gear operating speed of 1330 rpm, using three- to six-million cycles for high loads and 12- to 15-million cycles for low loads.

Low overhead and accessibility enable ARL Penn State to operate its gear test capabilities at a lower cost than industry. As a result, excellent gear and gear materials testing services are now available to manufacturers who cannot afford an in-house gear test facility.

Phase Shift Optical Triangulation

The key to drivetrain performance, in terms of noise and wear, is gear geometry accuracy. Both accuracy and cost, in turn, are dependent on the ability to perform precise measurements quickly and cheaply. Current practices employ coordinate measuring machines (CMMs) to inspect gears. Although accurate, this method is slow and provides sparse data, since it is dependent on physical contact with the gear. In response to this problem, ARL Penn State developed a non-contact, high-speed precision gear measurement system with sensitivity equal to CMMs, but with much higher speed and spatial data density.

The Phase Shifting Triangulation system, as shown in its current configuration in Figure 2-2, measures a gear surface and compares it to a master gear profile. To date, a surface profile accuracy of one micron, and a speed of one tooth per second have been demonstrated. The system provides output as an analytical report of gear error and as a 3-D topographical map. Developed for the Marine Corps Naval Air Depot in Cherry Point, North Carolina, the system can generate a 1000 x 1000 data point map in one second. The Phase Shifting Triangulation System utilizes a field measurement technique based on a four-step phase shift to measure the deformation of a projected grating. The amplitude of the deformation of the projected lines (stripes) is indicative of the surface differences. This data density (1000 x 1000 points compared to 3 x 3 points for CMMs) provides sufficient information to allow accurate predictions of noise and wear to be made — a major step in cost and reliability enhancement.

To address real-world situations, ARL Penn State enhanced the Phase Shifting Triangulation system with a recovery technique called Multiple Exposure Illumination Compensation. This technique can compensate for dirt or bright spots, which are points on gears where no data can be collected. These spots appear as white outs (flares) on phase maps. By performing multiple exposures at lower and lower illumination levels, this technique ultimately obtains good data at some illumination level for every point on the gear. By compiling the various maps at these levels, a compensated phase map is produced.

The Phase Shifting Triangulation system built for Cherry Point is based on comparative measurements against a master. ARL Penn State is presently building a second system, based on an absolute measurement calibration, with a major supplier of gear inspection equipment. The current capability of inspecting spur gears will be expanded to include helical and spiral bevel gears. However, the system in its current configuration represents a major step forward in terms of speed, wear, and noise prediction, as well as the potential for affordability impact in drivetrain production.

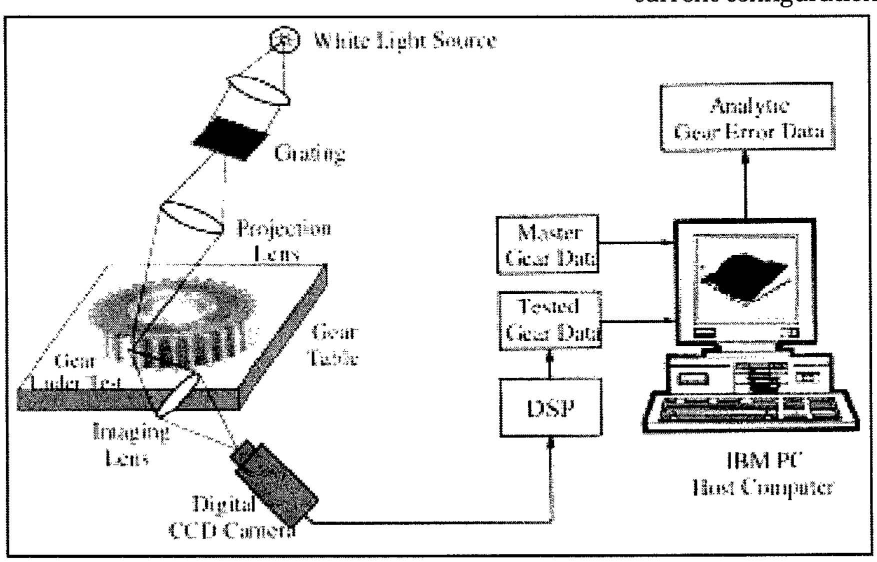


Figure 2-2. Phase Shifting Triangulation System

Portable Phase-Stepping Digital Shearography

The inability to detect subsurface flaws in composite materials under field conditions (e.g., onboard a carrier) often requires aircraft to be taken out of service and sent to a depot facility whenever damage is suspected. This procedure is expensive and detrimental to Fleet readiness. In response to this problem, ARL Penn State developed the Portable Phase-Stepping Digital Shearography system which can perform full-field, non-contact inspection of suspected damage to aircraft structure in situ.

Shearography is an optical interferometric technique which detects small, out-of-plane displacements. In detecting subsurface flaws, shearography systems rely on static or dynamic excitation (e.g., heat, internal pressure) to flush out flaws. The result is a fringe pattern whose anomalies display approximate flaw size and position. However, commercial shearographic systems produce qualitative results with low signal-to-noise ratio which results in low detection sensitivity. ARL Penn State's Portable Phase-Stepping Digital Shearography system utilizes optical phase-shifting, advanced digital signal processing and image processing techniques. As a result, this system provides detection sensitivity improvements of almost two orders of magnitude greater than commercial systems. The output is displayed as a real-time image of high resolution (1000 x 1000 pixels), capable of large area airframe nondestructive inspection.

The Portable Phase-Stepping Digital Shearography system is completely self-contained and can be operated by a single individual. Figure 2-3 depicts the system's schematic. The system also features a hand-held detection head which contains the optics, display, and containment for the vacuum system used to provide surface deflection. The operator holds the detection head (weighing less than 20 pounds) to the surface to be inspected, turns on the vacuum, and obtains the shearogram in real time. The laser source, vacuum source, and controller are connected to the head via an umbilical, allowing relatively unlimited access to the aircraft structure.

The Portable Phase-Stepping Digital Shearography system, as configured, is capable of detecting surface deformations with a sensitivity of 1/100th of an optical wavelength (five nanometers), which greatly increases the flaw detection capability. Inspection of a one-square foot area takes several seconds, an order of magnitude faster than traditional ultrasound techniques. The portability of the system allows the device to be used in nearly any environment including shipboard. ARL Penn State estimates the system will reduce annual maintenance costs by $240,000 per depot facility.

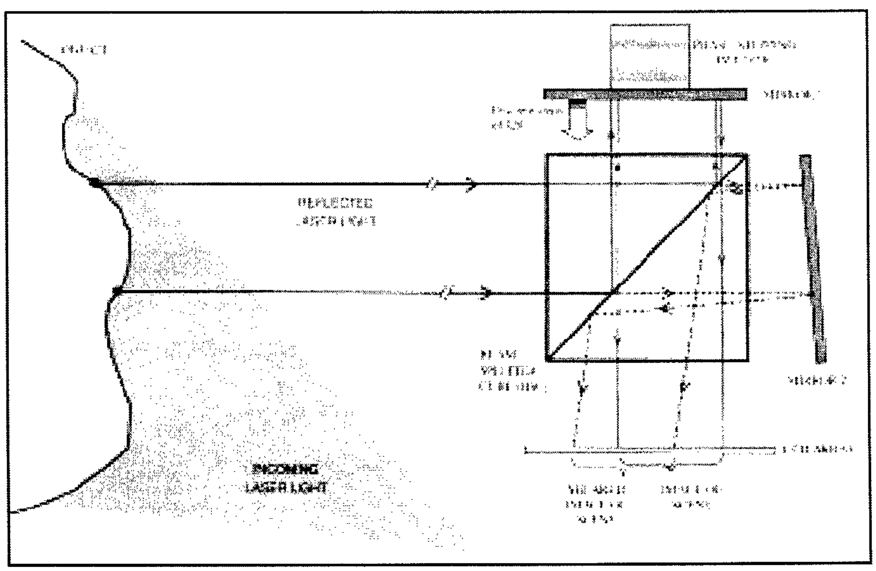


Figure 2-3. System Schematic

Production

Abrasive Flow Machining

The Naval Aviation Depot at Cherry Point, North Carolina always prepared its turbine blades for recoating by using an iterative, time-consuming nitric/hydrofluoric acid etch and manual media blast process. This expensive process generated hazardous wastewater due to the pH concentration and the presence of chromium. The Navy approached ARL Penn State to evaluate Abrasive Flow Machining (AFM) as an alternative to this process. The laboratory developed analytical techniques to optimize AFM's setup for removing thin coatings (two to four mils).

AFM removes very small amounts of surface material by forcing a highly viscous fluid or carrier, containing an abrasive, back and forth across the surface. The carrier behaves like a non-Newtonian fluid, making its flow difficult to predict and causing uneven material removal. A typical solution is to install spacers which limit the flow area and create an environment for consistent material removal. However, the success of this approach is by trial and error, and optimum material removal is not always produced. To resolve this issue, ARL Penn State developed a computational fluid dynamics flow model to predict the insert size and shape needed to produce optimum removal. The laboratory is also evaluating AFM as an alternative method for surface coating removal.

Approximately 100,000 to 200,000 turbines are stripped annually. By implementing AFM, ARL Penn State estimates that facilities could decrease cost by $30 per turbine ($3 to $6 million a year) and reduce hazardous wastewater by 500,000 gallons per year. The process is several orders of magnitude faster than current techniques of grinding, sandblasting or chemical etching and generates no environmentally hazardous waste stream.

Alternative Lubricants and Environmental Implications

At the request of the Navy, ARL Penn State performed a study on the use of alternate lubricants for MS 2190 TEP. This mineral oil is the most widely used lubricant within the Navy (12,000 gallons per vessel) and has the highest disposal volume at 2,700 gallons per base. In addition, 93% of DDG-52's specified lubricant is MS 2190, and 89% of this is used within drivetrain equipment and components.

ARL Penn State, in conjunction with Mobil Oil, tested mixtures of 70/30 blend synthetic polyalphaolefins (PAO 10 and PAO 18), both COTS Mobil synthetic oils. The new formulation, SHC 2190, is completely compatible with the mineral oil-based 2190 for ease and efficiency of substitution. The study also showed that SHC 2190 had superior performance and biodegradability compared to MS 2190, and its use resulted in reduced maintenance, less lubricant changeouts, lower failure rates, and fewer repairs. Although life-cycle costs are increased, SHC 2190 provides longer lubricant lifetime, increased equipment lifetime, extended operating limits, and reduced the amount of lubricant being disposed and met environmental compliance requirements.

Comparison testing is currently being performed at the Norfolk Naval Shipyard on four Monarch machine lathes (two with MS 2190 and two with SHC 2190). Periodic lubricant samples are being tested and evaluated by Mobil Oil.

Ausform Finishing

Ausforming is a hardening process that produces very high strength steel. The process converts metastable austenite to martensite by quenching, and increases material strength up to 50% without any loss in ductility. The strengthening is proportional to the degree of deformation, and higher strength persists after the tempering operation. Ausform strengthening is also a result of fine structural changes rather than macroscopic grain and shape effects. Ausform finishing integrates three commonly used gear manufacturing processes: induction heating, martemping (or marquenching), and gear roll finishing. ARL Penn State's Drivetrain Center (DTC) consolidated these processes into a single, in-line automated manufacturing operation that is capable of finishing spur and helical gears to a quality rating of 12 or higher per the American Gear Manufacturers Association.

Conventional gear processing consists of carburizing and slow cooling. Gears are reheated, quenched to martensite, and case-hardened to a Rockwell hardness of over 60. However, residual stress caused by these processes distorts the dimensional accuracy that is needed for useable gears. In response, ARL Penn State developed a machine that integrates ausform strengthening with precision gear-roll finishing. Two power-driven, master precision gear-rolling dies made of hot, high-hardness tool steel are used to produce precision-finish gears. The process involves contour austenization of the case-hardened gear teeth and quenching to metastable austenite, followed by plastic deformation of the gear-tooth surface layers to final dimensions and quenching to martensite. Ausrolling integrates the heat treatment and hard-finishing processes into a single, in-line automated manufacturing operation, which eliminates grinding and refrigeration requirements.

ARL Penn State consistently produces ausformed gears with a surface finish of four to six micrometers compared to eight to ten micrometers using traditional honing methods. Ausforming also improves the bending strength of critical sections on spur and helical gear teeth. DTC is currently conducting a study on surface enhancement techniques using ausforming and multilayer coatings to improve the surface fatigue life of rolling element bearings.

Cold Gas Dynamic Spraying

ARL Penn State developed and implemented a Cold Gas Dynamic Spraying (CGDS) process for applying special coatings on various substrates. This low-temperature deposition process can produce coatings from one micrometer to 20 millimeters by accelerating particles at sufficiently high velocities. This approach produces initial embedding into the substrate as well as subsequent solid-state welding on the deposited material.

The gas temperature for CGDS ranges from 0° C to 800° C. The process imposes minimum residual stress on the substrate due to low-temperature application, and produces a high degree of adhesion to the substrate which makes thick coatings possible. The coating properties are similar to those of powder properties. CGDS uses a high deposition rate, provides high material use efficiency, and produces freestanding structures for rapid prototyping. By using this simple, efficient, and low cost method, ARL Penn State can apply special coatings such as AlSi and AlSiC on 2024-T6 substrate. Others coatings including Al-12Si+SiC, AA5083+SiC, AA6061+SiC, and Al-Ce-Cr-Co+SiC have been deposited on various substrates such as metal, alloys, glass, ceramics, and polymers.

ARL Penn State installed an automated spray cell for the CGDS process. This initial capital equipment investment was less than $150,000. In the AAAV program, CGDS provided deposition of wear-resistant aluminum composite coating, which replaced the 4140 steel wheel and reduced more than 20% of the wheel's weight. This process is adaptable to wheel repair and rework. Other commercial applications of CGDS include wear-resistant coating on steam pistons and track components; soldering and brazing coatings; valve seat cladding; and heating element deposition on glass. CGDS proves to be a low cost, high technology material deposition process for low-temperature applications of selected coatings.

Laser Cladding

Many techniques are currently used in industry to repair and restore damaged/worn surfaces of high value components. Some of these long-standing practices are being phased out due to the inherent environmental problems they produce. Chrome plating is no longer acceptable due to its environmental restrictions. Cladding the damaged surface also has drawbacks and restrictions depending on component, use, and specifications. Conventional cladding requires high heat input which often leads to part distortion and material malformation. This process also involves pre-machining of the surface so that a layer of weld can be applied and machined to the original specifications of the component.

ARL Penn State has taken the lead in the development of laser cladding. This method uses low heat input which eliminates residual stress and distortion problems. By providing a true metallurgical bond with the parent material of the component being repaired, laser cladding produces minimal material malformation between the filler material and substrate of the component. ARL Penn State proved this technology by testing various filler materials, substrates, and lasers. This ability to clad a wide variety of filler materials and base materials has also been demonstrated and successfully transferred into industry for real-world applications.

One example involved a local manufacturer who had to go offshore to clad weld its valve body seats. This process required an extensive post-weld machining operation when the valve body seats were returned, resulting in a significant loss of high value material. Working with this manufacturer, ARL Penn State developed and transferred a process that enabled the manufacturer to perform the machining operation by using laser cladding. As a result, the manufacturer realized significant cost savings and was able to maintain and control the entire process in-house. ARL Penn State is continuing to find applications and benefits of laser cladding, and is working with customers to help them transition this technology into everyday operations.

Laser Induced Breakdown Spectroscopy

At the request of the Navy, ARL Penn State researched ways to measure lead, cadmium, and chromium in paint slated for removal from dry dock ships and scrapyard items. Current methods for measuring metal and metal oxides in paint include chemical spot tests which produce results difficult to quantify; off-site laboratory techniques which are time-consuming and require careful sample extraction; and x-ray fluorescence which is susceptible to errors from metal substrates and situations where lead-free paint layers obscure underlying leaded paint layers. This method also uses radioactive sources that must be federally registered and maintained.

ARL Penn State's research led to the development of the Laser Induced Breakdown Spectroscopy (LIBS) system. This portable system focuses a laser pulse of sufficient power density onto a sample, whereby the area is volatilized into a microplasma and analyzed by a spectrometer. Unlike most methods using atomic emission spectroscopy, the sample is ionized and evaluated in one step with little or no sample preparation. The system can also accurately determine the metal content in multilayered paint. Results are displayed instantly in real time on the system's computer screen. The LIBS system has been successfully tested at Puget Sound Naval Shipyard.

The LIBS system's portability makes it easy to use in dry docks and scrapyards. The ease of accurately testing paint and obtaining real-time results will greatly benefit the shipbuilding industry. ARL Penn State currently has a few companies interested in manufacturing the LIBS system.

Overspray Capture System

ARL Penn State developed an Overspray Capture System which entraps the gaseous emissions from paint coating operations on large, relatively flat surfaces. Known as overspray, these emissions are a function of the transfer efficiency of the coating operation. In standard spray painting operations, 40% to 70% of the coating material dispensed from the spray gun fails to reach the substrate being coated. Overspray from anti-fouling coatings (containing copper) for ship hulls is considered to be particularly toxic in marine environments.

By modeling the fluid dynamics of the spray system, ARL Penn State designed a shroud enclosure to capture overspray. The captured emissions can then be treated by conventional means or via the laboratory's Overspray Treatment System. The Overspray Capture System will be used in conjunction with the Navy's Automated Painting, Capture, and Treatment System, which semi-automates the coat application process for ship hulls.

Although most volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) are emitted during the curing stage following spraying, overspray does contain some VOCs and HAPs. By capturing overspray, the system reduces total emissions to the environment by about 25%. Negative pressure, total containment of ships being coated is the current method of controlling the release of toxic particles into the environment. This procedure usually costs about $1 million per containment. The Overspray Capture System could reduce or eliminate this cost.

ARL Penn State designed its system to capture more than 95% of overspray with the shroud positioned up to ten centimeters from the substrate's surface. This design allows the equipment to operate on curved surfaces as well as on surfaces with projections of less than ten centimeters. ARL Penn State estimates that the Overspray Capture System will enable ship hull maintenance operations to meet particulate and emission standards at a lower cost than current methods. This technology may also be applicable on other large, relatively flat surfaces such as large aircraft, water towers, bridges, and buildings.

Paint Shelf Life Monitoring

Many materials used in government and industry contain hazardous components. Once the posted expiration dates are reached, these items are removed from inventory and disposed of as hazardous waste. In 1997, the Department of Defense (DOD) spent $230 million on handling and disposal costs for expired materials. However, studies indicate that in many cases these materials are still acceptable for their intended functions. At the request of the Navy, ARL Penn State began searching for a low cost means of monitoring the usability of these materials.

ARL Penn State chose silicon alkyd haze gray paint as a likely candidate to monitor because of its wide use in the Navy and its similarities with other commonly used paints in the military. The laboratory determined that conductivity and polarization, as a function of frequency, reliably indicate the condition of paint. As a result, ARL Penn State developed the Micro-Electro-Mechanical Sensor (MEMS) chip which can determine the usability of paint in a sealed can.

Immersed in the paint, the MEMS chip performs this function in real time, and can be mass produced at a very low cost. The chips would be placed inside paint containers during manufacturing. Using remote sensors, personnel could read the chip and determine the status of the paint without opening the can and testing the contents.

The MEMS technology has the potential to avoid significant handling and disposal costs for hazardous waste. In addition, paint could be validated beyond the posted expiration dates to extend the shelf life of stock. To date, only a prototype chip has been built by ARL Penn State.

Repair and Refurbishment of Fatigue Limited Structures

Cladding is a long-standing process used to repair and restore damaged/worn surfaces of high value components. Depending on the area being refurbished, a pre-machining step is required to prepare the surface so that a layer of weld can be applied and machined to the original specifications of the component. The process involves many hours of preparation to ensure that the repair does not distort other surfaces of the part during the welding and final machining processes. By using laser cladding, ARL Penn State can apply layers of metal to the part in a much more controlled manner. Distortion during welding is also minimized due to the localized application of heat and cladding materials. Primarily used on steel substrates, laser cladding is accepted and qualified by industry.

ARL Penn State took this technology one step further. The laboratory expanded the laser cladding's applicability by tailoring the process to other surfaces (e.g., titanium structures, aluminum alloys 6061 and 7075). Working closely with the Navy's Keyport facility in Washington, ARL Penn State developed and demonstrated the successful use of this technology on real components. One application involved repairing the O-ring surface of a torpedo's aft fuel tank, which would have cost $65,000 to replace. In another case, ARL Penn State restored the sealing surfaces of four, newly-fabricated forward fuel tanks that were damaged during shipment. Without this technology and its successful application, these components would have been scrapped.

The Keyport facility also acquired a laser system to perform in-house repairs on components of various alloys. ARL Penn State is supporting the initial laser workcell startup at the Naval facility, and will concurrently develop and qualify processes for repair of other components. These efforts will enable high-value, torpedo components to be repaired and refurbished. In the past, scrapping was the only alternative since the replacement costs of these items were high due to low volume and time constraints. The successful implementation of this advanced laser cladding technology will continue to expand as more processes are developed.

Risk Assessment Modeling

Based on its own concerns and those of the Southwest Marine, San Diego, and Puget Sound Naval Shipyards, ARL Penn State submitted a bid to the National Shipbuilding Research Program (NSRP). The bid's purpose was to design a scientifically-based tool that shipyards could use for negotiating National Pollution Discharge Elimination System (NPDES) limits. This tool would assist the shipbuilding/repair industry with NPDES permits and compliance; standard settings; and risk management.

ARL Penn State enlisted help from the National Steel and Shipbuilding Company (NASSCO) in San Diego, California and professors from the Pennsylvania State University. Together, the group identified current and future NPDES requirements for shipbuilding and repair facilities, and developed a computer model to predict shipyard flow; transport of contaminants; and an ecological, risk-calculator computer model.

The NPDES Risk Assessment Model consists of three, interlinked models that predict the dispersion of shipyard pollutants in a bay/estuary and the resulting environmental risk from the pollutants. Although currently based on NASSCO and the San Diego Bay, this risk model can be adapted for use by any shipyard. By Spring 1999, the Risk Assessment Model will be issued to NSRP for review, and then become available to all shipyards.

Spray Forming of Aluminum Alloys

ARL Penn State operates a 6,000-square foot Spray Metal Forming (SMF) facility that houses a pilot production plant with extrusion capability. The SMF facility also provides alloy preparation and refining capabilities, and reduces manufacturing costs by eliminating the intermediate processing steps for some alloys.

Spray metal forming is a rapid material manufacturing process that atomizes a metal stream with inert gas. A mixture of liquid and solid particles is deposited onto a collection plate or mandrel in the form of billet, tube, or sheet/plate. Characteristics of the deposited material include being relatively void free; and having low oxygen content, no inclusion directionality, and ultra-fine size grains. The deposited material can either be used in the as-sprayed condition or processed further through forging, extrusion, semisolid forming, or rolling. The spray metal forming process produces metallic structures with isotropic, crystallographic, and finer-size grains than traditional casting. In addition, the process can fabricate new compositions and structures which are impossible by conventional ingot or powder metallurgy processes.

The SMF facility produces many products including ultra-high-temperature (700°F) alloys; high-strength aluminum alloys (850 MPa); ultra-low-density aluminum alloys (Al-High Li); high strength, corrosive-resistant aluminum alloys (Al-Zn-Mg-Cu); wear-resistant aluminum alloys; and metal matrix composites. The facility also employs the spray metal forming process on a variety of applications. One application involved integrating the process with the fan stator design, development, and testing of jet engines (e.g., Joint Strike Fighter project), which reduced engine weight and improved the service life of new engines. In another case, the process reduced unit weight and provided wear- and corrosion-resistant materials for tracked road vehicles (e.g., AAAV program). Other potential applications for spray metal forming include automotive chassis; engine and brake components; aircraft wheel and brake assemblies; recreational sport equipment; computer disk components; and cryogenic tanks.

The SMF facility produces materials with unique metallurgical characteristics using advanced alloy systems with a proven fabrication process. Through its efforts, the facility transforms new material concepts into real-world applications.

Management

Electronic Manufacturing Management Information System

ARL Penn State is a partner in the re-engineering of the Navy Centers for electronics and electro-optics manufacturing. As such, the laboratory developed and implemented the Electronic Manufacturing Management Information System (EMMIS). This electronic, web-based network supports the Electronics Manufacturing Productivity Facility in its mission to assist the electronics manufacturing industry. ARL Penn State houses the server.

Rather than centralize all operations at one facility, EMMIS's organizational paradigms distribute operations to personnel at many organizations across the country. At ARL Penn State, the Information Systems (IS) Department develops informational systems that support the business needs of these organizations. The IS Department accomplishes this task by using industry standard, Internet-based web and database technologies, customized to provide the needed functions. The success of a distributed-organization approach relies on effective communication. Individuals must be able to access current information regarding schedules, projects, customers, technical information, and technology transfer efforts from all locations. EMMIS accomplishes this task through:

- Searchable information databases for ongoing and completed projects (e.g., project plans, milestones, budgets, reports);
- Input and retrieval capabilities to locate data on customers and business partners (e.g., capabilities, interests, interactions with the organization); and
- Server-based scheduling for personal calendars, business development efforts, and travel.

EMMIS operates on a relational database server that is connected to the Internet via custom-developed web applications. This setup allows users to input information and retrieve data while being connected anywhere on the Internet. Most software applications reside on the users' personal computers, so ARL Penn State controls the distribution of release versions through mutual agreements. All data is centrally located on the EMMIS server, where it is managed and backed up on a regular basis. The system also contains a private site with restricted access, and a public site which is available to everyone. Users access the server via web browser platforms, and special purpose client software is provided for applications such as calendar systems or custom input/reporting functions. Other EMMIS capabilities include an online help system; a project management system; a technical library with online ordering and downloading of publications; a central management of customer data and interactions; a calendar; e-mail capabilities; and current schedules for training opportunities and training site information.

EMMIS represents a significant advancement in virtual user communication and networking. The system provides access to information from any location and increases network efficiency. In the past, users could only download or distribute information at their offices, which diminished the value of time-related data. EMMIS' scalable architecture allows new capabilities to be developed by using the latest software tools and standards as they become available. This approach reduces obsolescence, promotes the sharing of data, and maintains security among users.

Problem Solving Focus

For more than 50 years, ARL Penn State has been in the problem-solving business. This particular focus serves the Navy in the areas of Naval warfare and undersea technology, and helped the Pennsylvania State University become the number-two ranked university in industrial research and development (R&D). Since funding mainly comes from government sources, most of ARL Penn State's efforts are oriented toward developing and improving technologies that enhance manufacturing practices, and reduce risks associated with fielding high quality, reliable Navy and Marine Corps weapon systems. ARL Penn State also devotes a substantial portion of its efforts to working with industry and transferring dual-use technology to the commercial sector.

To best serve its clients' needs, ARL Penn State enlists many highly developed approaches for identifying opportunities where the laboratory can apply its assistance. For example, the Navy uses formal systems to identify and prioritize manufacturing technology and repair technology issues. ARL Penn State works closely with the Navy as these issues develop and then proposes projects, based on the University's capabilities and technical expertise, to address these issues. The laboratory also maintains communication with Naval shipyards, depots, and centers to learn about problem areas that it may be able to resolve. Often, these organizations approach ARL Penn State because of its reputation and/or proven expertise in solving technical and manufacturing related problems. Many problems identified in this manner become funded projects.

ARL Penn State's charter includes supporting technology transfer to enhance the United States' economic competitiveness and, in this role, work closely with the private sector to identify opportunities for applying expertise/technology from the defense sector to commercial applications. The laboratory accomplished these objectives by interacting with industry through many consortia, partnerships, and alliance relationships. ARL Penn State is also part of the University's and the State of Pennsylvania's economic development thrust, which responds to the needs and problems of industry through a technology transfer network. This network includes ARL Penn State; cooperative extension and continuing education programs; the Pennsylvania Technical Assistance Program; small business development centers; Pennsylvania Industrial Resource Centers; and Ben Franklin Partnership programs. Most of these programs concentrate on small- and medium-sized businesses. In many cases, companies either directly come to ARL Penn State with problems/requests or are referred to the laboratory by other organizations. Frequently, state-funded programs help pay for the assistance provided to these companies by ARL Penn State.

By applying its broad array of technical expertise and resources, ARL Penn State has solved hundreds of problems. These success stories play an important role in enhancing the readiness of the Navy and Marine Corps, as well as improving the Nation's industrial and technological competitiveness. ARL Penn State's ability to identify and successfully tackle critical problems helps to sustain growth for itself as well as build a solid reputation for the University.

Public Relations and Publications

Effective communication is an essential part of achieving success in technology transfer and in sustaining and developing a business base. ARL Penn State communicates with the users and sponsors of its programs and resources by employing low cost, but highly effective methods. Most public relations and publication costs are compensated through overhead funds. As a result, ARL Penn State is motivated to develop inexpensive, effective outreach methods. However, the laboratory does receive some publication and outreach funding from the Navy's Manufacturing Technology (MANTECH) program in support of MANTECH technology transfer projects.

ARL Penn State's website (http://arl.psu.edu) is the most extensive source for up-to-date information. Virtually everything going on at the laboratory is covered on the website, and many of the publications and papers that ARL Penn State produces can be accessed here. In addition, ARL Penn State's personnel attend numerous forums, symposia, and workshops. This face-to-face interaction with potential clients and sponsors typically leads to the development of funded projects or new relationships for the laboratory. Another valuable, low cost approach used by the laboratory is to publish articles in its clients' and sponsors' newsletters, publications, and websites as well as in professional and technical publications.

In addition, ARL Penn State produces many informative publications on its programs, capabilities, and resources which are distributed to a closely managed and carefully updated mailing list. Although ARL Penn State employs low cost methods for production, publication, and distribution, the quality is excellent. The annual report of the Institute for Manufacturing and Sustainment Technologies (iMAST) is an attractive, full color, spiral-bound publication that costs only $400 to produce. The laboratory uses low cost, high quality trifolds to provide updates and publicity information on its individual technologies, programs, projects, resources, and capabilities. Another excellent publication is the iMAST newsletter which is paid for by the program sponsor at a production cost of only $2,000.

ARL Penn State capitalizes on various cost-effective methods to get the word out. The laboratory minimizes publication and outreach costs, while achieving maximum impact. This approach is a key factor contributing to ARL Penn State's effectiveness and success.

Teaming Skills

ARL Penn State recognizes the importance of teaming with industry and government partners; other university organizations; and all levels of its own organization. Aside from being a good business practice, teaming supports technical excellence and innovation, and facilitates the political and funding support necessary to obtain and sustain projects.

ARL Penn State has been very successful in bringing together leading organizations from government, industry, and academia to achieve leadership focus in specific technology sectors. Examples include the Laser Processing Consortium with more than 20 world-class companies in this field, and the Electron Beam-Physical Vapor Deposition (EB-PVD) Consortium with nearly 70 world-wide members who work together in the development and commercialization of advanced EB-PVD coating technology. Developed in the former Soviet Union, this technology was transferred to ARL Penn State through a collaborative research effort funded by the MANTECH program. Consortium members benefit from the development of new coatings from this MANTECH-funded technology transfer effort, and share resources and results for new coating fabrication technology. Another example is ARL Penn State's Gear Research Institute, which leads and performs research, development, and testing to support the gear industry as well as promotes education and technology transfer.

Through effective teaming and partnerships, ARL Penn State established a strong, competitive position for winning new projects. This approach sets up extensive linkages and relationships that encourage new growth for the laboratory. Recently, ARL Penn State won a Navy contract to develop a national electro-optics center, in part, because of the high quality of the team which was assembled for the proposal. Successful teaming strategies represent a key factor in ARL Penn State's position as a leading facility for technical excellence and in providing new business development growth opportunities.

Technology Transfer and Deployment

Technology Transfer and Deployment (T^2D) is a principal mission of ARL Penn State which is firmly embedded in its culture and operation. The laboratory's charter promotes technology transfer for economic competitiveness, and supports congressional and DOD mandates in the transfer of federally-funded technology to the commercial sector. Technology transfer projects range from providing COTS technology implementation assistance for productivity enhancement to implementing advanced technologies for new product or process development.

ARL Penn State and the Pennsylvania State University developed many technologies under federal projects and non-sponsored departmental research. The laboratory's relationships with small companies; its teaming skills with government, industry, and academia; and its problem-solving focus have all consistently led to effective T^2D. In addition, ARL Penn State continues to expand and upgrade its facilities, and develop new strategic government and commercial alliances. The laboratory hosts national symposia highlighting areas of technical expertise, and sponsors detailed, hands-on workshops for technology transfer to government and industry.

Technology transfer efforts are particularly concentrated on, but not limited to, providing economic development support for industry within the State of Pennsylvania. These efforts include transfer of Navy, DOD, and other government-funded technology development; direct technical support and proposal development; direct contract support; and training and continuing education. Industrial development programs take several forms. ARL Penn State can perform work-for-other efforts under a contract or do the work itself under a contract to industry. Other forms include consortia programs and projects, and state-funded efforts.

State funding and assistance programs offer ARL Penn State the opportunity to work with small, entrepreneurial companies in ways that lead to the development of thriving companies and new industries. One example is GEO-Form, a small, environmental engineering startup in Girard, Pennsylvania. ARL Penn State helped GEO-Form design and manufacture a biological reactor system prototype for municipal wastewater treatment to meet the Pennsylvania Department of Environmental Resources' certification trials. The result was an all-composite design that outperformed existing and competing systems manyfold, and met performance and cost requirements. Each component is produced by the most efficient, available manufacturing process. The system is now being installed at all highway rest stops in Pennsylvania, and the company is expanding worldwide.

ARL Penn State's T^2D efforts have achieved success in many technology areas such as shearography, spectroscopy, turbine blade stripping, laser cladding, spectro/paint characterization, fatigue amelioration, and welding of lightweight structures. Industrial success stories include laser cutting and welding of aluminum for automotive applications; laser cladding of struts for fabrication and repair of heavy equipment components; laser welding of medical equipment; laser cutting of bicycle frame components; development of lightweight composite frames for high performance bicycles; and improvements in laboratory centrifuges. Details of these and similar success stories can be found on MANTECH's website at http://mantech.bmpcoe.org/successes and on ARL Penn State's website at http://www.arl.psu.edu.

Section 3

Information

Test

Advanced Gear Steels

Since the 1970s, significant R&D efforts have been invested in rotorcraft turbine engine materials and processing technology. These sustained efforts yield substantial improvements in power-to-weight ratios as well as power ratings of rotocraft turbine engines. However, technological advancements in materials/manufacturing processes used in the main transmission subsystem and its components greatly lag behind engine performance. As a result, rotocraft engines are routinely derated to match the main-drive transmission due to limitations.

The potential exists to enhance the overall operational capabilities of rotocraft by improving ratings and power density of main-drive transmission subsystems to match engine power. The primary goals needed to achieve reasonable parity in the rotocraft drive-system performance (engine to rotor) include a 25% reduction in rotocraft drive-system weight, a 10-decibel reduction in transmission-generated cabin noise, a 100% increase in meantime between removals, a 50% reduction in maintenance, a 10% reduction in acquisition cost, and a 25% reduction in production lead time.

The Rotocraft Materials Coalition was established among ARL Penn State, air vehicle manufacturers, turbine engine manufacturers, steel producers, and gearbox/component manufacturers. The group's objectives are to develop an advanced materials database for advanced, hot-hardness, drive-system component steels; conduct heat studies and associated specimen testing to optimize processing parameters and reduce manufacturing cost; and conduct gear testing to evaluate fatigue and scoring behavior.

Through its efforts, the Rotocraft Materials Coalition is making advancements in gear steels. Additional improvements are being made to reduce the weight and volume of drive-system dynamic components and lube/cooling systems, to lower support costs and life cycle costs, to improve the drive-system power density, and realize a multifold extension in drive-system component life due to increased strength and durability of advanced steels.

Advanced Modeling as a Knowledge Base

Modeling is an integral part of ARL Penn State's six-layer hierarchy for integrated predictive diagnostics. This process translates the sensing observables from a physical model with machinery phenomena effects. The development of model-based prognostic capability for CBM requires a proven methodology to create and validate physical models which capture the system's dynamic (vibratory) response under normal and faulted conditions.

In heavy duty and high performance power transmission systems, the rotary elements can be driven to catastrophic failure through various mechanisms. Subsystem component defective material and/or normal wear can lead to fatigue stress cracks. Damage initiated by transient load swings, due to larger magnitudes and higher-than-expected amounts of intermittent loading cycles, can also occur in a system when operational performance limits are chronically commanded. For most systems, operational demands prescribe a slow evolution (compared to operational speed or length of a given machine service event) in material property and/or component configuration changes. Therefore, the potential exists to track the fault through the filter of the system's behavior via its vibratory response.

The uniqueness of a fault's system-perturbing force, caused by the nature of a fault's physical mechanism, is of primary importance in identifying a signature in the vibratory response of a system. Faults occur at the weakest links in the physical load path that transmit the largest amounts of power and experience the largest, local stress variations due to dynamic loading. The load path in power transmission equipment can be complex; however, it may be identified as traveling through a few common components (e.g., gears, rotary shafts, rotary bearings, machine housing/frames). In terms of life-cycle fatigue behavior; faults/failures in gear pairs; rotary shafting; and bearings, the outcome is understood, but dynamic response and tribological information are lacking for machines operated to failure. This shortcoming motivated ARL Penn State to develop the MDTB. The laboratory uses this test bed facility to provide transitional failure data on gearboxes.

ARL Penn State's effort consists of computational and experimental work to correctly characterize the dynamic response. Currently under consideration by the laboratory is preservation of salient-relative dynamic features to capture and aid in a comprehensive understanding of deficiencies in current, macro-fault characterization models. This gearbox system model will also serve as a numerical study test bed to aid in optimal (or development of a best) sensor location strategy for CBM. Drive, misalignment, rotating unbalance loads, and some operating constraints will be assessed and estimated from experimental MDTB operating and transitional test data. Computational modeling efforts include finite element modeling and experimental identification/characterization of system modal and transfer characteristics. Analytical dynamic models of gear mesh, rotating shaft, and bearing faults will be adapted for integration and inclusion into an overall system model as nonlinear system perturbation forces.

Multisensor Data Fusion for Improved Fault Detection and Diagnostics

Multisensor data fusion is a continuous process dealing with the association, correlation, and combination of information from multiple sources. ARL Penn State is using this process to achieve refined condition estimation of machinery and to complete timely assessments of resulting consequences and their significance. This emerging technology is also being applied to DOD areas (e.g., automated target recognition, battlefield surveillance, guidance/control of autonomous vehicles) and non-DOD areas (e.g., monitoring complex machinery, medical diagnostics, smart buildings).

Data fusion techniques come from a wide range of disciplines including artificial intelligence and statistical estimation. By combining data from multiple sensors and related information from associated databases, these techniques achieve improved accuracies and more specific inferences compared to methods that use a single sensor. While data fusion is not a new concept, the emergence of new sensors, advanced processing techniques, and improved processing hardware make real-time fusion of data increasingly possible.

Until recently, DOD primarily used data fusion systems for target tracking, automated identification of targets, and limited automated reasoning applications. Renewed interest by DOD has changed data fusion technology from a loose collection of related techniques to an emerging, true engineering discipline with standardized terminology, techniques, and systems design principles. Techniques to design (or fuse) data are drawn from a diverse set of traditional disciplines including digital signal processing, statistical estimation, control theory, artificial intelligence, and classic numerical methods. In principle, fusion of multisensor data provides significant savings over single source data. Besides the statistical advantage gained by combining same-source data, the use of multiple types of sensors may increase the accuracy with which a quantity can be observed and characterized.

In 1996, the Joint Directors Laboratory Data Fusion Working Group was established to improve communications among military researchers and systems developers. The group's initial effort to codify the terminology related to data fusion resulted in the creation of a process model for data fusion and a data fusion lexicon. The Data Fusion Domain (Figure 3-1) is a functionally-oriented, process model of data fusion, and intended to be very general and useful across multiple application areas. This model identifies the processes, functions, categories, and specific techniques applicable to data fusion. The most mature area of data fusion processing is Level 1 which uses multisensor data to determine the position, velocity, attributes, and identity of individual objects or entities. Levels 2 and 3 are currently dominated by knowledge based methods such as rule-based blackboard systems. These systems are relatively immature with numerous prototypes. Level 4 assesses and improves the performance operation of an ongoing data fusion process, and has a mixed maturity.

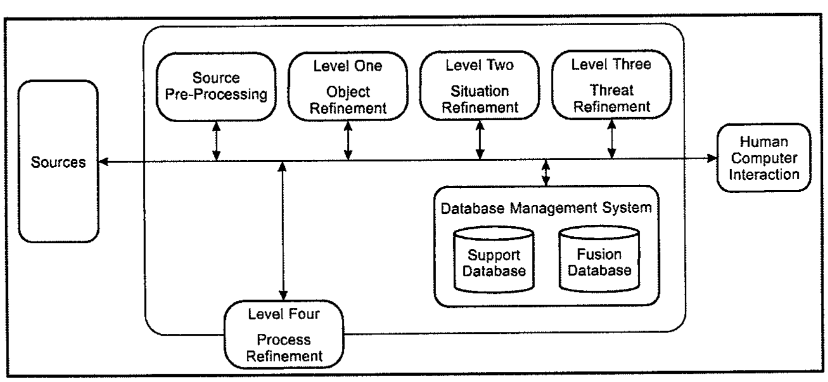


Figure 3-1. Data Fusion Domain

The data fusion community is rapidly evolving, and ARL Penn State is among the leaders. Significant investments by DOD have resulted in rapid evolutions of microprocessors, advanced sensors, and new technologies which, in turn, create new capabilities to combine data from multiple sensors for improved inferences. Applications are now entering the CBM area. Implementation of such systems requires an understanding of basic terminology, data fusion process models, and architectures as demonstrated by ARL Penn State.

Pareto Analysis Strategy

The Pareto principle states that 20% of the causes usually account for 80% of the effects. This distribution is typically the case in process and product improvements. Observations often show that the majority of problems stem from relatively few causes. At ARL Penn State, attention is being focused on maintenance activities with the greatest effect on asset performance, availability, and safety, while diverting energy away from those activities with little or no effect. A careful observation of the Pareto effect provides valuable insight in the development of an effective strategy for maintenance activities in a given application. Pareto analysis that uses Pareto diagrams, cause and effect methods, and histograms can intensify critical areas for which concentration of improvement efforts yield the most valuable returns.

Creating a Pareto chart as an aid to designing or improving a maintenance strategy begins by identifying different categories of failure causes and compiling various failure effects, such as cost and downtime contributed by each category. These categories are then arranged in a bar graph in descending order from largest to smallest contributor. A cumulative failure curve is superimposed onto the graph. By locating the area where the curve begins to level out (knee), users can identify the contributors of most problems. If a knee region is not readily determined, the user should identify the group of categories which make up at least 60% of the failures. ARL Penn State compares the indications of this chart to the distribution of effort in the current maintenance plan.

ARL Penn State is currently working with a consortium of companies to demonstrate the applicability of integrated prognostic health management technology for designing a new generation, turbofan fighter engine. A Pareto analysis was employed to help identify the appropriate application of wireless-distributed sensor, vibration-based health monitoring for the engine. The scope of the task was defined to include the engine main bearing and accessory gear train systems. Information on the failure modes for these systems was primarily gathered from engine manufacturer field service representative reports, as well as meetings and conversations with engine support and design engineers. Safety and asset availability were priority considerations; therefore, failures that led to in-flight emergency and abort events were compiled into one Pareto chart. Failures leading to engine removal were compiled into a separate chart. Another chart was created to show the distribution of all types of failures over the different failure modes in order to reveal those contributors deserving priority attention due to the number of failures.

Although ARL Penn State's chart did not match the typical 20%-80% Pareto distribution, the analysis did suggest categories which merited prioritized attention, and the most effective application of vibration-based health monitoring could be assessed. The analysis further suggests that a large majority of maintenance effort could have been avoided with an accurate, automated isolation of observed, fault condition sources. A change in maintenance procedures would be the most appropriate solution based on this analysis.

ARL Penn State's study exhibits a strong understanding of the value of Pareto analysis toward effective maintenance strategies. The benefits to the manufacturing industry to use Pareto analyses in designing maintenance and other quality improvement strategies can be realized by focusing efforts on those activities which yield the most beneficial results.

Reliability Centered Maintenance

Reliability Centered Maintenance (RCM) is a proven technique to reduce overall maintenance costs and analyze the functions of systems. Developed by the aerospace industry, RCM provides a logical method to identify failure modes; criticality of these failures; proposed procedures to address the consequences of these failures; and recommendations regarding the design of the system. This technique does not assign a task to a problem, but rather looks at the outcome of the failures.

Over the years, maintenance practices evolved from traditional repair-upon-failure to preventive maintenance to condition centered maintenance. Although preventive maintenance has advantages over run-to-failure techniques (e.g., lower operating costs, higher equipment availability, improved equipment reliability), this practice still incurs unnecessary costs.

In some cases, scheduled preventive maintenance allows inspection/maintenance tasks to be performed even though a component may not require them.

The latest maintenance philosophy is the use of CBM. Here, current sensor technology combined with low cost computing power enable maintenance decisions to be made based on a system's sensor measurements. Combined with RCM's failure modes effects and criticality analyses, condition monitoring offers the potential to provide substantial reductions in maintenance costs, improved performance of equipment, and better teamwork among operating personnel.

RCM can be implemented in a facility by using various software programs. For example, ARL Penn State conducted an RCM study to analyze ships' service gas generator sets for the Navy. This study identified potential areas where sensors can monitor critical system components such as bearings, gears, and motor/generators. The results of ARL Penn State's study supports the design for a wireless, data acquisition system to accomplish machinery component and system health monitoring of generator sets. RCM studies traditionally result in the delivery of a maintenance plan; however, the inclusion of condition monitoring promotes further reductions in maintenance labor costs by replacing some scheduled maintenance tasks with on-condition tasks. RCM is the latest technique to develop a cost effective system for a plant-wide maintenance program.

Shaft Torsional Vibration Analysis

ARL Penn State uses shaft torsional vibration analysis to detect and measure minute torsional vibrations (twists) which occur during shaft rotation. The laboratory's advances in this technique greatly enhance the ability to detect shaft and coupled load defects, which aid in characterizing the condition of machines and equipment.

When a shaft is turning at a constant speed, the modulated twist rate is so minute that it is undetectable with conventional sensory techniques. Traditional techniques use sensors to measure the flex and bend, harmonics, and torque of shafts. None of these have the ability to detect the minute changes in torsional vibration, especially when the shaft is operational and coupled to a load. ARL Penn State developed an extremely sensitive measuring technique that uses a laser light source and a photosensitive transducer probe to read the encoded tape applied to a rotating shaft/coupler being measured. Information obtained from the probe is first fed through an analog incremental demodulator, and then a digital signal processor for presentation. The shaft torsional vibration analysis can also detect and measure the low frequency signal and amplitude that represents a fingerprint for a continuously rotating healthy shaft. When minute alterations occur to the shaft or coupled load, the fingerprint also changes.

Another significance of shaft torsional vibration analysis is its applicability to the CBM community. Parameters which were previously nonexistent can now be analyzed. This technique not only detects minute alterations to the rotating shaft, but to the coupled load which may prove even more significant (e.g., in the detection of defective blades in turbine engines and power generators). Further refinement, analysis, and characterization are being pursued by ARL Penn State to predict the specific defects occurring within a shaft and coupler system.

Statistical Characterization of Failure Data

CBM is the philosophy of repairing/replacing a part or component based on observed objective evidence. Integral to this philosophy is the early detection and recognition of impending mechanical failures. Cost benefits of CBM, especially for safety or increased equipment usage, are also an important aspect of reliable maintenance programs. One of ARL Penn State's contributions to CBM involves using statistical characterization of failure data to evaluate and develop early warning alarms for impending mechanical failures.

ARL Penn State built upon previous research to determine the effectiveness of using wide band signal processing algorithms (e.g., the continuous wavelet, transform-based, diagnostic algorithms adapted to the problem of gear-tooth crack detection). After initial trials with the wavelet algorithms proved successful on generated transitional data, ARL Penn State continued its research on related but separate paths. In particular, the laboratory addressed the importance of fault-detection threshold settings and false-alarm performance. A combination of analytical and empirical data analyses were performed to establish a methodology for deriving user-specified, false-alarm performance for the wavelet design fault monitor.

ARL Penn State transferred this technology to NASA Ames Research Center's applied research wind tunnel platforms, where a similar analysis will be performed on the Center's data. This application represents the value of advanced sponsored research for the purposes of benefitting government and industry. Future work will be directed toward searching for best processing algorithms for early detection, detection performance, and computational efficiencies; developing discrete wavelet transform research on acoustical emission data; analyzing wavelet coefficient data with neural networks; addressing shaft torsion analysis data; developing multisensor fusion algorithms; and supporting reasoning algorithm development.

Transitional Failure Data: Acquisition and Management

CBM involves more than just conducting tests on machines or determining failure/reliability measurements. Instead, true CBM identifies and tracks observables to detect faults, and can relate these variables to the overall condition and useful life of equipment. To support its expanding CBM efforts, ARL Penn State established four facilities including the Mechanical Diagnostics Test Bed (MDTB). The MDTB facility was constructed to provide data on commercial transmissions as their conditions deteriorate from new to faulted to failure.

The generation of continuous run/good-to-bad gearbox transitional data will be used to determine appropriate data fusion and approximate reasoning techniques which will result in identifying and detecting precursors to failure. The MDTB also provides a test and evaluation vehicle for emerging prognostics, time-to-failure/remaining-life prediction algorithms and advanced sensor development (Figure 3-2). The test bed consists of a 30-horsepower (hp) drive motor coupled through a torque cell to the input of a 5- to 20-hp gearbox, and a 75-hp load motor coupled through a torque cell to the output of the gearbox. Instrumentation consists of thermocouples and infrared sensors for gearbox and motor temperatures; accelerometers for gearbox and driveline vibration signatures; acoustic emission sensors for gearbox impact energy events; dielectric and debris monitors for gearbox oil quality and sampling; input/output torque cells for gearbox torque/efficiency monitoring; and current and power factor instrumentation for motor monitoring.

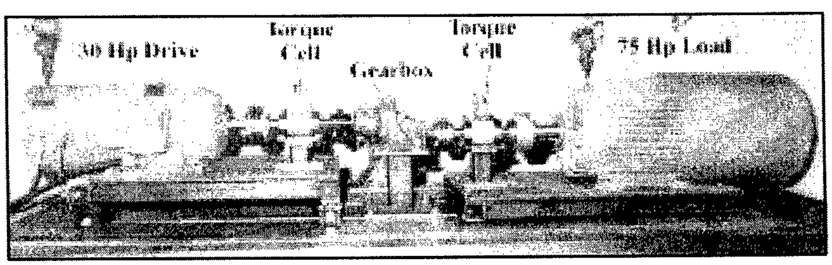


Figure 3-2. Mechanical Diagnostics Test Bed

Although advanced methods in maintenance technology are still in their infancy, multiple new technologies are emerging and being applied to maintenance and mechanical diagnostics problems (e.g., advanced detection methods for temperature, oil analysis, and vibration signal processing). A limiting factor in the further development of CBM continues to be a lack of high fidelity data of faults as they initiate and evolve. ARL Penn State's MDTB effort addresses this shortcoming by providing a realistic test stand that effectively represents an operational environment and by its ability to bridge the gap between typical, university-scale, test environments and the real world. The MDTB is evolving into a method to generate realistic data sets for use in the development of CBM technology with the intention of making these sets available to industry and other researchers.

Key to the current research project is the ability to accurately monitor a system via sensors; process and fuse sensor data; and model and predict the evolution of fault conditions. The MDTB directly accommodates the need for transitional data, which tracks faults from initiation to an ultimate failure mode. Cost savings potential is quite attractive for CBM practices in the manufacturing and operational environment. A 1989 study, associated with the maintenance strategies used on rotating equipments in plants, estimated the normalized costs per year at $18 per hp for corrective, $13 per hp for preventive, and $10 per hp for CBM.

Production

Barstow Air Treatment Performance Study

To meet environmental regulations, facilities with paint booth operations must treat their air emissions to remove harmful organics (e.g., VOCs, HAPs). The Marine Corps Maintenance Center in Barstow, California uses a large paint booth operation which produces 45,000-cubic feet per minute (cfm) of emissions. The Center employs a vendor-supplied Air Pollution Control System (APCS) that combines ozone, ultraviolet (UV) light, and carbon filters to treat the emissions. However, the Marine Corps wanted to determine the overall VOC removal performance and regeneration efficiency of its system, and verify the scalability of system upgrades and improvements. The Center approached

ARL Penn State because of its experience in testing air pollution control technologies using ozone, UV light, and carbon absorption to destroy organics.

ARL Penn State set up a 2,500-cfm, pilot-scale treatment unit at its laboratory to test the ability of scaling up the results to the Barstow system. Similarities between the pilot-scale treatment unit and the Barstow system include:

- A gas phase photolytic reactor that uses UV light and ozone filters to initiate photolytic, photocatalytic, and free radical reactions to oxidize contaminates;
- An aqua reactor consisting of a counter-flow packed bed scrubber, a mist air dispersion unit, and an oxidizing water treatment tank to absorb and oxidize contaminates; and
- A granular activated charcoal (GAC) unit which absorbs contaminates.

ARL Penn State discovered that the regeneration of the GAC became non-functional over time. This conclusion severely reduced the treatment efficiency of the APCS. The laboratory projected that scaling the findings to the full-scale APCS in the Barstow system would have the same result. To verify the prediction, ARL Penn State tested the Center's APCS, and reported a similar degraded performance over time. Under sustained operations, the GAC was not regenerating properly. The Marine Corps Maintenance Center is reviewing methods to modify its APCS, otherwise the Center will have to severely curtail its paint booth operations to meet emission standards.

F/A-18 F404 Engine Fretting and Low-Cycle Fatigue Study

Fretting and low-cycle fatigue occurs when two surfaces come into contact under pressure with a high frequency of reciprocating motion. This type of fatigue is adversely affecting the compressor and fan sections of the F404 engine in the F/A-18. The current configuration of the titanium fan blade and the titanium fan disk provides for a copper-nickel-indium coating on the blade root. When this coating fails, the top surface material's properties change and lead to cracking at the interface. If not discovered in time, this wear can lead to catastrophic failure of the compressor section.

ARL Penn State initiated the F/A-18 F404 Engine Fretting and Low-Cycle Fatigue Study to evaluate the failure mechanisms and duplicate them in a laboratory environment. The study will determine fretting and damage modes of current titanium dovetail/disc components for establishing a baseline failure configuration. After establishing this configuration, an optimum coating and/or coating process will be developed and implemented at manufacturing facilities and repair depots. This approach will eliminate/minimize fretting and low-cycle fatigue at the blade-disk interface. ARL Penn State will be evaluating the optimum coating and/or coating process in the laboratory and in actual Fleet testing.

A shot peening process for the blades is also being evaluated. Intermetallic layers at the blade root sections have been identified through the study. The presence of this layer occurred from the unexpected diffusion of titanium and copper-nickel-indium coatings, and could cause the failures. The issue is currently being investigated.

Functional Gradient Thermal Barrier Ceramic Coatings

By using an Electron Beam-Physical Vapor Deposition (EB-PVD) system and the flexibility it offers, ARL Penn State developed a process for producing functional, gradient thermal barrier coatings (TBCs). Prior to EB-PVD, TBCs were applied by using a flame spray process. However, this process did not provide a metallurgical bond to the substrate, and was inconvenient at best for turbine blades where cooling passages became filled with spray material. By contrast, EB-PVD allows for a uniform deposition of multiple materials in varying concentrations to form a gradient of properties, thereby optimizing substrate protection and thermal coefficient match.

Figure 3-3 depicts the EB-PVD system. The system contains six 45-kilowatt electron beam guns. Typically, two guns are used to heat the target component, while the other four are used to selectively evaporate the three ingots of coating material. The ability to vary the material choice, target position and motion, and the gun energy provides a wide spectrum of possible coating configurations. The following is an evolution of TBC configurations:

- Lamellar TBC Produced by Plasma Flame Spray — Poor grain structure, voids, and low adhesion to the substrate.
- EB-PVD — Columnar structure for high radial strength.
- EB-PVD with Graded Coating — Improved substrate thermal match and adhesion.
- TBC with Alloying — Introduction of secondary elements (tantalum) to engineer voids and lower thermal conductivity.

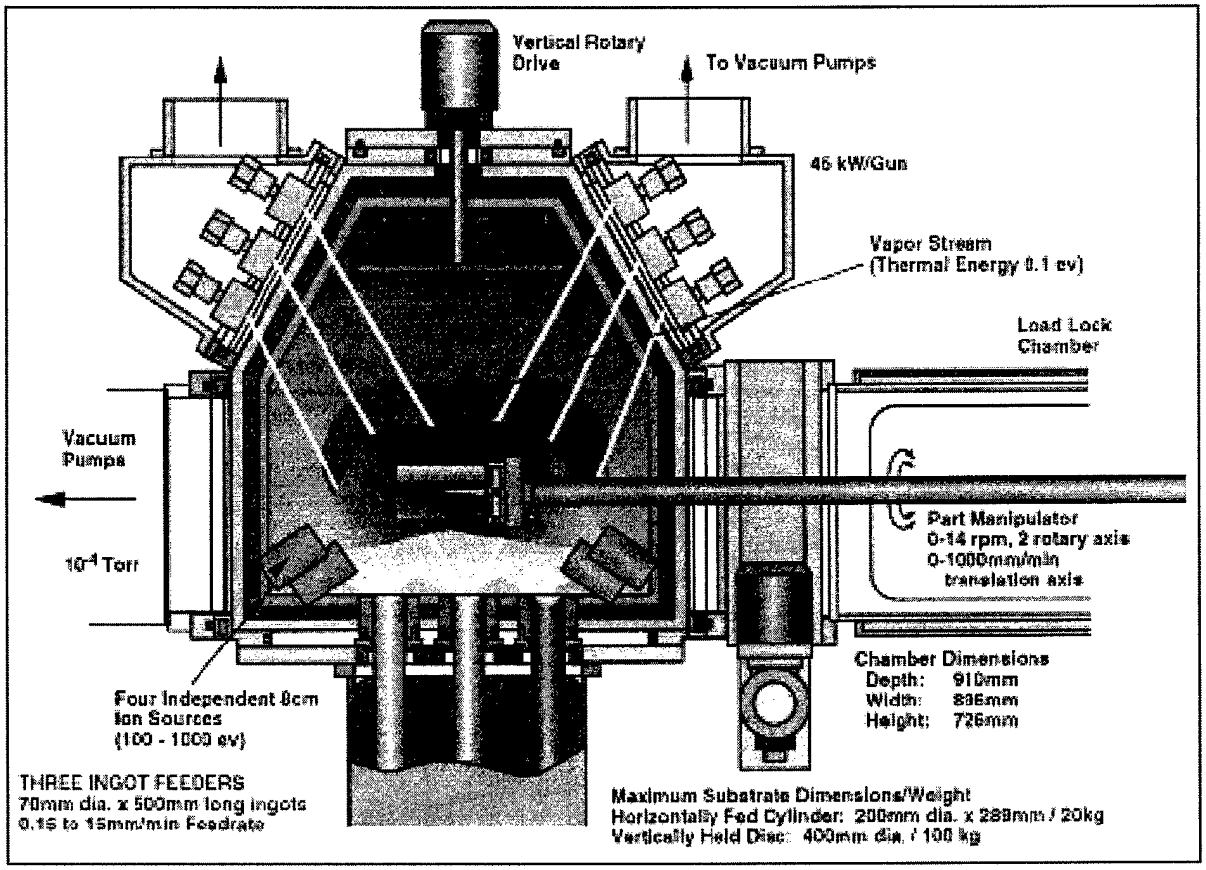


Figure 3-3. Electron Beam-Physical Vapor Deposition System

- Multilayer Columnar TBC — Discontinuities introduced by removing and reintroducing target from chamber, but provided even lower thermal conductivity.

Inherent advantages of EB-PVD for TBCs include high deposition rate (14 kilograms per hour); potential for multilayered or gradient coatings in metals, ceramics, and composites; flexibility allowed for engineered material configurations; and ability to accommodate large-size components (1 meter x 1 meter x 1 meter). These features also provide superior adhesion; thermal matching between substrate and graded coatings; and lower thermal conductivity. As a result, TBCs improve component life and engine performance; increase operational temperature from 1300°C to 1500°C; create a reduction in required active cooling; and reduce specific fuel consumption of approximately 1%.

Global Workpiece Positioning System

ARL Penn State developed a non-contact Global Workpiece Positioning System that can be defined at a qualification station, and then identified on a machine station. This approach allows part features to be recognized and machined with respect to the system. This virtual part reference system also eliminates the use of a physical surface as datum, which is sensitive to dirt, chips, and burrs on the machine station. The presence of these items typically result in an out-of-alignment condition. This shortcoming has been identified as a production problem for precision transmission gearbox assemblies. ARL Penn State's non-contact approach is based on incorporating several nonintrusive transmitting devices on the part as well as a system that identifies the precise location of the devices on the part. The nonintrusive measurement is accomplished by using a laser-triangulation based measuring system.

Previous efforts to fabricate transmissions were ineffective due to the high labor, intensive cost factor. Today, transmission assemblies still employ a high degree of custom assembly practices. Gearboxes are assembled and tested for proper gear seating, and shimming practices are commonly used to improve gear-tooth engagement. These practices continue to be used because current manufacturing processes are still unable to machine critical transmission components to the level of accuracy and precision needed to standardize assembly practices, based on true interchangeability. The key deficiency is that the current practice of fixturing and work holding utilizes physical surfaces for datum reference. This practice has remained unchanged since the advent of modern machining practices.

The setup time on precision gears and transmission housings can take as long as two eight-hour shifts before final machining is initiated. Recent efforts to reduce setup time have resulted in excessive scrap rates. By using its Global Workpiece Positioning System, ARL Penn State can define the virtual datum of the part, and reduce the setup time for precision machining of transmission housings. The system identifies a virtual part datum on the machine tool after the part has been clamped, but before machining starts. The Global Workpiece Positioning System compensates datum errors and clamping influences in precision transmission component machining. The virtual datum provides a means to allow the machine datum to adjust for alignment compensation and, therefore, produces a more precise machined part.

ARL Penn State demonstrated the feasibility of using a non-contact measuring system to define the virtual datum for machining parts. The implementation of the Global Workpiece Positioning System is in process at a contractor site.

Hard-Metallic-Ceramic Multilayer Coatings

ARL Penn State developed a process for producing a hard-metallic-ceramic multilayer coating for cutting tools. This process, based on ion beam-assisted EB-PVD, indicates a tool life extension of 600% to 800% compared to uncoated tools. Earlier research by ARL Penn State produced a tool life extension of 400% by utilizing single layer TiN coatings which were applied using the EB-PVD system.

Wear resistance in cutting tools depends on four factors:

- Material crystal structure — covalent and ionic bonds
- Grain size — nano and submicron sizes
- Interface structure — coherent, semi-coherent, and incoherent structures
- Composition — TiN/TiB2; TiC/TiB_2; TiC/Cr_3C_2; and TiC/Al_2O_3

This multilayer coating process controls and tailors these factors in an optimum manner by which the engineered, multilayer material stops cracks at the material interface. This approach also eliminates a major failure mode for hard coatings.

Developed by ARL Penn State, the EB-PVD system has a unique configuration. The system contains six 45-kilowatt electron beam guns. Typically, two guns are used to heat the target component, while the other four are used to selectively evaporate the three ingots of coating material. The part is manipulated in the resulting vapor stream. The speed of rotation and translation are also determining parameters in the process.

By producing hard-metallic-ceramic multilayer coatings for tools, ARL Penn State demonstrated substantial tool life extension. Significant cost savings have resulted from an increase in tool utilization and a decrease in downtime for tool changeouts. The multilayer coating also resists wear through a unique mechanism by which the material interface serves as a crack stop.

Laser Assisted Forming Process

Funded by the Defense Advanced Research Projects Agency, in 1996 ARL Penn State teamed with Rocketdyne, the Massachusetts Institute of Technology (MIT), Boeing, and the Norfolk Naval Shipyard to develop predictive capabilities for laser forming of hull components through the use of numerical modeling. The Laser Assisted Forming (LASFORM) process relies on controlled localized heat to create stress states that result in semi-predictable distortion. This process primarily involves angular distortion with the amount of distortion related to the power of the laser; the processing speed; and the thickness and composition of the material being formed.

The primary goal of the team was to demonstrate the LASFORM process on an actual ship component. A hull component, representing a Naval warship, was chosen for the demonstration based on its relatively complex shape and compound curvature. However, a thinner material (compared to an actual hull component) was selected for the demonstration, to enhance handling during presentation but not diminish the proof of the process. The team successfully demonstrated the LASFORM process by forming a part that provided a fair representation of the desired geometry in approximately 14 hours with 20 passes of the laser over the part. As a result, ARL Penn State established a proposed program that involves the integration of

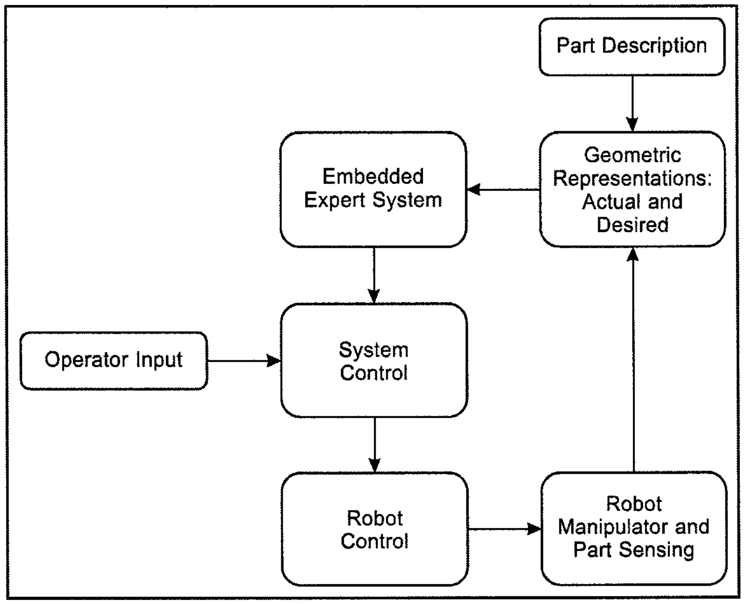


Figure 3-4. Schematic of Laser Assisted Forming System

robotic, sensor, and embedded expert systems based on CAD-generated data (Figure 3-4).

The LASFORM process' benefits include improved dimensional tolerances, repeatability, lower costs, and quality control. Considerable effort is being made in Europe to refine the LASFORM process due to its many benefits.

Laser Cutting and Welding of Lightweight Structures

ARL Penn State is a leader in developing laser technology processes for cutting, welding, and fabricating lightweight structures. Components formerly made from castings are now being examined as candidates for fabrication using laser technology processes. In most cases, this technology reduces weight without sacrificing the functionality or design requirements of the finished product. Depending on the application, a laser formed fabrication can usually be produced at equal cost to conventional casting.

Laser fabricating takes advantage of common shapes of material (e.g., plates, pipes) to produce components that normally require a casting process. The machining times for finished products are significantly reduced due to the near-net shape of the fabrication. Using these laser fabrication processes, ARL Penn State demonstrated the process on several projects where weight and functionality were critical factors. The laboratory designed and fabricated lightweight panels which are being used on a Naval warship as an antennae support platform. The use of these panels resulted in a weight reduction of 20,000 pounds for this foundation platform. The panels can also be used on a variety of applications without sacrificing structural stability and strength, while providing a significant reduction in weight.

ARL Penn State transferred this technology to two Naval shipyards for further applications. By leading the way in the development of laser fabrication processes, ARL Penn State is helping industry find better ways to produce quality products at competitive costs.

Laser Free Forming of Structures

Over the years, ARL Penn State has led the way in laser free forming technology and continues to apply this process on different shapes by using various alloys. Sponsored by the Office of Naval Research, ARL Penn State has been developing laser processing and equipment to refine laser free forming technology. The goal is to establish faster deposition rates than those currently achieved. The use of laser free forming provides greater material homogeneity as well as higher mechanical properties than those found in a typical casting of the same material. There is also more uniform corrosion and cavitation resistance. The work at ARL Penn State has been devoted primarily to titanium free forming of large (up to one meter dimension) structures.

One material currently being examined is nickel-aluminum-bronze (NAB). NAB has been shown to exhibit significant improvement in its microstructure when the material is laser free-formed. This material has many applications and is commonly used in sea water piping, fittings, bushings, sleeves, and propellers. NAB's resistance to corrosion, cavitation, and biological fouling make it a primary material for use in the shipbuilding industry. Large components, such as propellers, are generally fabricated from castings and exhibit significant in-homogeneity due to the chemical variations and cooling rate differences of the cast material. In addition, porosity, cracks, and voids are not visible during the manufacturing process, and can only be detected using extensive nondestructive inspection. However, even this procedure does not always reveal the flaws which can cause a component to fail during operation.

Laser free forming of various materials has many applications throughout industry, and ARL Penn State is developing many of them. As this technology continues to evolve, it will become a more commonly used process.

Laser-Liquid-Solid Interaction Technique

ARL Penn State developed a novel process for synthesizing nanoparticles and nanotubes/nanorods. The process utilizes a Laser-Liquid-Solid Interaction (LLSI) which produces uniformly small particles from the precipitation of a solution. Applications are possible in many disciplines:

- Biotechnology, as delivery vehicles for medications and genetic therapies
- Electronics, in solder pastes and small feature size metallizations
- Structures, where single crystal microstructures are required

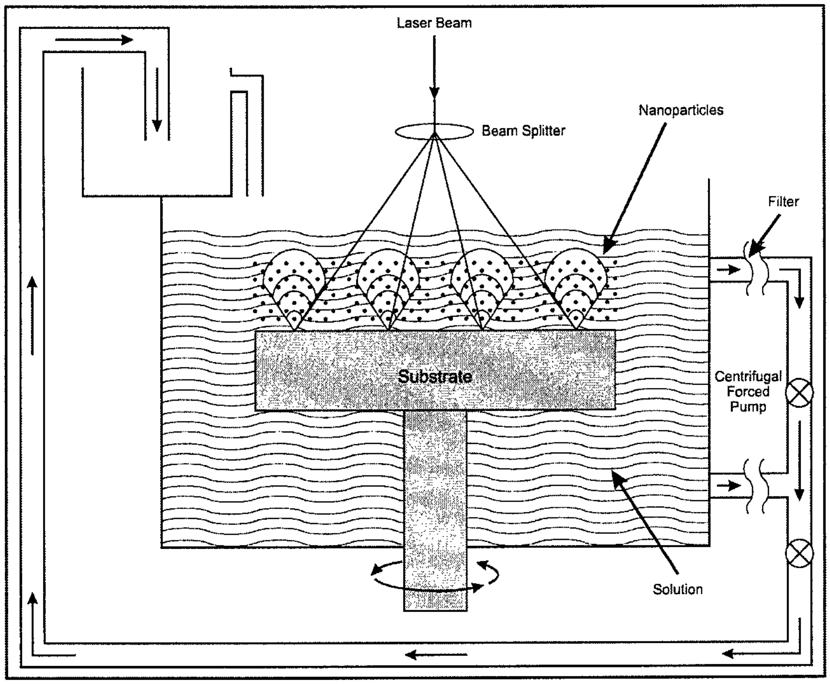


Figure 3-5. Synthesis of Nanoparticles by Laser-Liquid-Solid Interaction

Primary attributes in the utilization of nanoparticles are a uniformly small size (less than 100 nanometers) and a reasonable production rate. The LLSI process accomplishes both of these characteristics. Previously available techniques have many shortfalls in producing nanoparticles including:

- Mechanical Milling — Produces micron-level particles but not nano-level ones, and creates a high level of contamination from ball bearings.
- Chemical Precipitation — Difficult to control particle size and shape, and produces hazardous waste solutions.
- Laser Ablation — Has an extremely slow production rate of grams per day.
- Thermal Spray — Uses a slow process to produce micron-level particles, and some contamination exists.
- Spray Pyrolysis — Produces porous particles which are desirable only in ceramic applications.
- Laser Pyrolysis — Has a slow production rate, but is useful for iron oxides.

By contrast, the LLSI process provides uniform nano-level particles of good density and at a rate several orders of magnitude greater than most competing techniques. The synthesis of nanoparticles using the LLSI (Figure 3-5) is simple in principle. Pulsed laser energy is impinged on a rotating target substrate formed from a high-conductivity material such as copper. The target is heated, creating a localized plasma in the nearby solution, such as $AgNO_3$ and water (a waste product of the photographic process). The localized plasma interacts with the solution, precipitating nanoparticles of metal (silver in this example). The figure also shows how a beam can be split into multiple beams, which speeds production and demonstrates a continuous flow process to enrich and re-circulate the solution.

The LLSI technique can be tailored to alter/control size and production rate by varying four key parameters: wavelength and energy of the laser; interaction time as determined by pulse length; composition and concentration of the pre-cursor solution; and thermal conductivity of the target substrate. This process also provides the ability to create nanotubes by using higher viscosity solutions, which prevents precipitated particles from washing away, thereby linking them to form tubes or rods in situ. The addition of a surfactant as a catalyst, such as ethylene glycol, increases formation and serves as a polymer coating to protect reactive materials such as aluminum from oxidizing. The inclusion of a second material in the solution makes its possible to form alloys of otherwise immiscible materials such as AgNi.

ARL Penn State's efforts show the clear advantage of the LLSI process over competing techniques. The LLSI process provides uniformly small nanoparticles from a variety of materials; promises a production rate two orders of magnitude beyond most competitors; enables particle production and coating to occur simultaneously; allows deposition to occur at room temperature; and is tailorable across a number of parameters. In addition, the process does not require a vacuum; provides nanotubes as well as particles; produces alloys of otherwise immiscible materials; and can be made continuous.

Overspray Treatment System

ARL Penn State designed a system to treat emissions from ship hull coating maintenance operations. Many paints used on hulls contain VOCs and HAPs, which are emitted during the application and curing stages of coating operations. Small particles containing copper (from anti-fouling coatings) can also be emitted during the application stage. Environmental agencies closely regulate VOCs, HAPs, and particulates. Therefore, the particles must be treated before they can be released into the environment.

One way to capture emissions is to totally contain the ship being serviced under negative pressure. A potentially more efficient method is to use ARL Penn State's Overspray Treatment System. This treatment system uses a standard wet filter as well as an adsorption biofilter to reduce emissions to compliance levels.

Currently, ARL Penn State is preparing to build a prototype of the Overspray Treatment System for further testing.

Treating Bilgewater Using Critical/Super Critical Carbon Dioxide

ARL Penn State is working with the Navy to derive a better way of treating contaminated bilgewater in deployed Naval ships. Bilgewater from ships usually contains hydrocarbons from minor leaks and spills of hydraulic fluids, fuels, and lubricating oils. Because of this contamination, bilgewater must be treated before being discharged. The Navy's primary treatment method is a parallel plate separator, which uses polymer beds designed for a 15-parts per million (ppm) discharge. The compliance goal is five ppm, with the system actually achieving approximately 100 ppm. Problems associated with the current system include performing periodic, manual underway changeouts; storing spent polymer onboard; and transporting spent polymer back to port which creates additional disposal costs. In addition, parallel plate separators continue to be plagued by biological growth that releases noxious hydrogen sulfide gas and clogs the separation panels.

ARL Penn State is evaluating the use of Critical/Super Critical Carbon Dioxide (C/SCCO_2) to treat bilgewater. The investigation is using a laboratory-scale C/SCCO_2 system to extract contaminants from simulated bilgewater. ARL Penn State will focus on optimizing process conditions for effective counterflow extraction of oily residues, as well as characterization of surfactant effects. The ultimate goal is to develop an automated system that meets the five-ppm discharge requirement; reduces labor and life-cycle costs; eliminates underway changeouts of expendables with minimal underway maintenance; and requires no additional onboard storage space.

Currently, ARL Penn State is in the exploratory development stage on the C/SCCO_2 system. Although the laboratory-scale model has been tested and is highly effective and does not introduce additional contaminants to the waste stream, it still needs to go through a prototype stage and prove itself aboard ship.

Management

Technology Transfer of Condition Based Maintenance Technology

Currently, no true market pull exists for Condition Based Maintenance (CBM) technology, also known as Operational Equipment Asset Management (OEAM). ARL Penn State is among the leaders in the CBM technology community that notes the importance of transferring OEAM technology from the laboratory to the workplace. Taking the lead on this effort, ARL Penn State established the OEAM Consortium made up of government and industry representatives who are striving to channel this technology through a proposed effort, which remains to be funded.

As it stands, the market for OEAM requires a few commercial industries and military contractors to pursue this technology individually through a variety of resources, yielding different levels of OEAM maturity. With the present state of OEAM technology and resources, this approach is far from an efficient and effective way to acquire technology. However, most potential customers do not yet recognize or understand the impact that OEAM technology can have on their operations, and although the level of maturity is progressing rapidly, it is considered high risk. These factors contribute the lack of a market pull for OEAM technology. Therefore, the need continues to exist for innovative technology transfer initiatives as proposed by ARL Penn State and the OEAM Consortium.

University Relationship

ARL is an integral part of the Pennsylvania State University, which gives the laboratory an extended capability to manage and perform interdisciplinary research. ARL Penn State is the largest of the affiliated laboratories, centers, and institutes that make up the University's Intercollege Research Programs. The laboratory collaborates with various research faculty and facilities including the Colleges of Engineering, Science, and Earth & Mineral Sciences. The Penn State system serves more than 62,000 students, and produces numerous patents and inventions each year. In addition, the Penn State system has an annual operating budget exceeding $1.4 billion with a research program that receives nearly $264 million in federal, state, and private funds. Penn State is second only to MIT in industry-sponsored R&D, and ranks tenth among U.S. universities in total R&D expenditures.

The relationship with the University provides many advantages and greatly enhances the capabilities of ARL Penn State. One of these advantages is the availability of talented, highly motivated, and affordable researchers from the University's population. Of the 34 ongoing projects in ARL Penn State's iMAST program, 24 have students on their team, 14 use teaching professors, and five enlist teaching professors as principal investigators. As new opportunities arise or Naval needs are identified, ARL Penn State taps the resources of the various Colleges, such as getting assistance from the business school to help solve logistics problems for the Marine Corps.

Through its relationship with one of the country's largest and highly respected R&D-oriented universities, ARL Penn State has access to a vast array of resources and expertise which it draws on to support clients. This arrangement also proves to be a competitive strength to ARL Penn State in winning project awards and in attracting support/resources for its many successful programs.

Appendix A

Table of Acronyms

Acronym	Definition
AAAV	Advanced Amphibious Assault Vehicle
AFM	Abrasive Flow Machining
APCS	Air Pollution Control System
ARL Penn State	Applied Research Laboratory at the Pennsylvania State University
C/SCCO$_2$	Critical/Super Critical Carbon Dioxide
CAD	Computer Aided Design
CBM	Condition Based Maintenance
CFM	Cubic Feet per Minute
CGDS	Cold Gas Dynamic Spraying
CMM	Coordinate Measuring Machine
CORBA	Common Object Request Broker Architecture
COTS	Commercial-Off-The-Shelf
DOD	Department of Defense
DTC	Drivetrain Center
EB-PVD	Electron Beam-Physical Vapor Disposition
EMMIS	Electronic Manufacturing Management Information System
GAC	Granular Activated Charcoal
HAP	Hazardous Air Pollutant
HP	Horsepower
ICAD	IntelliCAD
iMAST	Institute for Manufacturing and Sustainment Technologies
IS	Information Systems
KBE	Knowledge Based Engineering
LASFORM	Laser Assisted Forming
LIBS	Laser Induced Breakdown Spectroscopy
LLSI	Laser-Liquid-Solid Interaction
MANTECH	Manufacturing Technology
MDTB	Mechanical Diagnostics Test Bed
MEMS	Micro-Electro-Mechanical Sensor
MIT	Massachusetts Institute of Technology
NAB	Nickel-Aluminum-Bronze
NASSCO	National Steel and Shipbuilding Company
NPDES	National Pollution Discharge Elimination System
NSRP	National Shipbuilding Research Program

Acronym	Definition
OEAM	Operational Equipment Asset Management
PAO	Polyalphaolefin
PPM	Parts Per Million
R&D	Research and Development
RCM	Reliability Centered Maintenance
SBD	Simulation Based Design
SMF	Spray Metal Forming
T^2D	Technology Transfer and Deployment
TBC	Thermal Barrier Coating
UV	Ultraviolet
VOC	Volatile Organic Compound

Appendix B

BMP Survey Team

Team Member	Activity	Function
Larry Robertson (812) 854-5336	**Crane Division** **Naval Surface Warfare Center** Crane, IN	**Team Chairman**
Cheri Spencer (301) 403-8100	**BMP Center of Excellence** College Park, MD	**Technical Writer**
	Condition Based Maintenance Team	
Larry Halbig (317) 891-9901	**BMP Field Office** Indianapolis, IN	**Team Leader**
Charles Goss (717) 394-2052	**MANTECH** York, PA	
	Environmental Team	
Elaine Geisler (909) 273-4991	**Naval Warfare Assessment Station** Corona, CA	**Team Leader**
Steve Hillenbrand (423) 632-8489	**Tennessee Valley Authority** Knoxville, TN	
	Metal Processes and Gears Team	
Ken Lee (909) 273-4998	**Naval Warfare Assessment Station** Corona, CA	**Team Leader**
Arnold Barnes (423) 576-2025	**Lockheed Martin Energy Systems** Oak Ridge, TN	
	Simulation Based Design Team	
Nick Tambakis (301) 403-8100	**BMP Center of Excellence** College Park, MD	**Team Leader**

High Energy Processes Team

Jack McInnis (703) 271-9055	**Production Technology, Inc.** Arlington, VA	**Team Leader**
Jack Tamargo (707) 642-4267	**BMP Satellite Center** Vallejo, CA	

Management and Technology Transfer Team

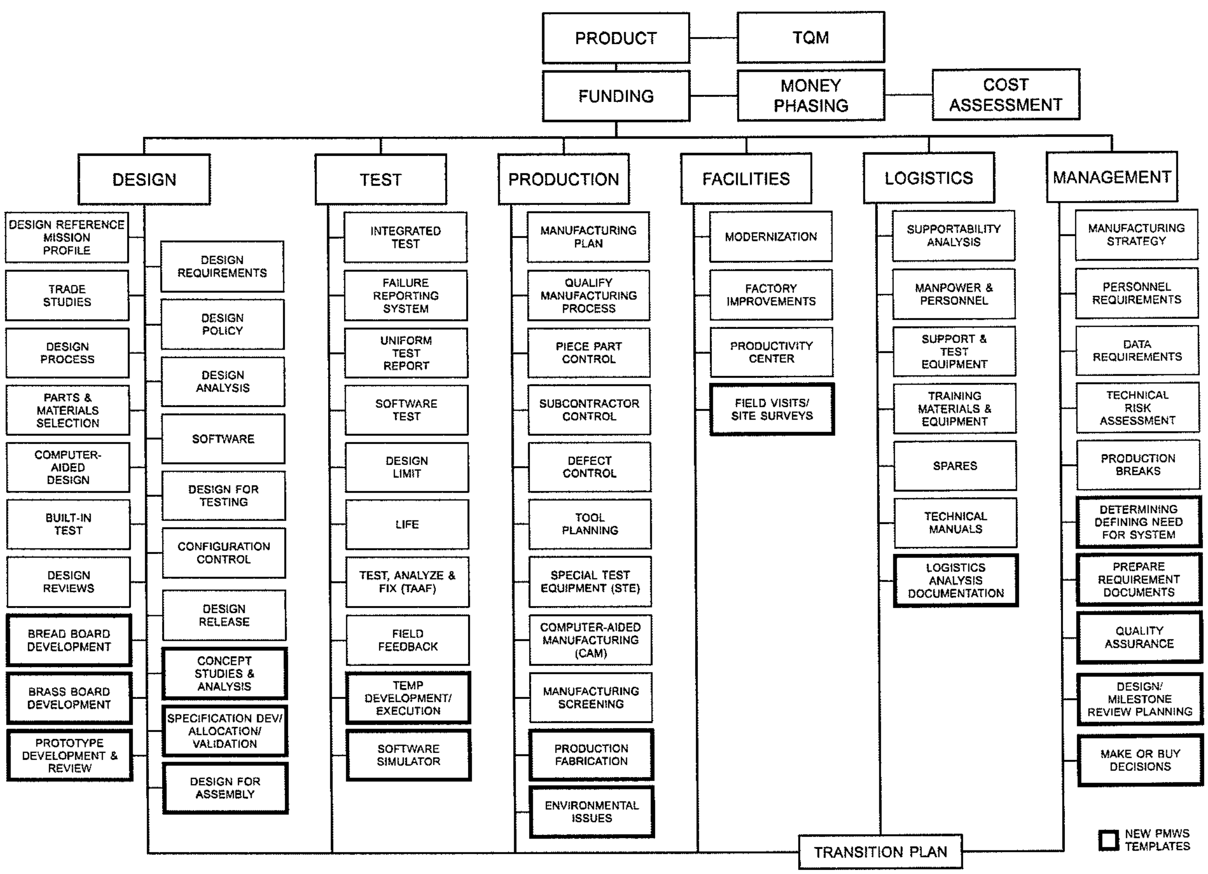
Rick Purcell (301) 403-8100	**BMP Center of Excellence** College Park, MD	**Team Leader**

Appendix C
Critical Path Templates and BMP Templates

This survey was structured around and concentrated on the functional areas of design, test, production, facilities, logistics, and management as presented in the Department of Defense 4245.7-M, *Transition from Development to Production* document. This publication defines the proper tools—or templates—that constitute the critical path for a successful material acquisition program. It describes techniques for improving the acquisition process by addressing it as an *industrial* process that focuses on the product's design, test, and production phases which are interrelated and interdependent disciplines.

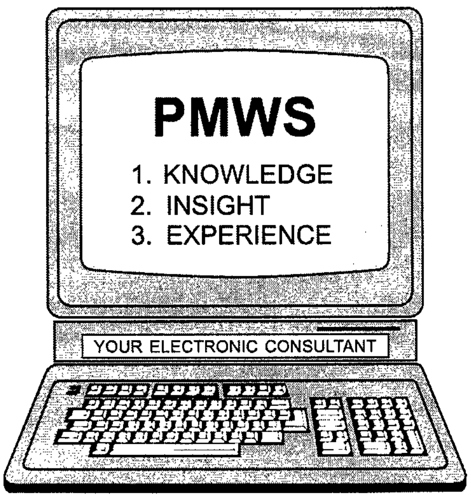
The BMP program has continued to build on this knowledge base by developing 17 new templates that complement the existing DOD 4245.7-M templates. These BMP templates address new or emerging technologies and processes.

"CRITICAL PATH TEMPLATES FOR TRANSITION FROM DEVELOPMENT TO PRODUCTION"



Appendix D
BMPnet and the Program Manager's WorkStation

The BMPnet, located at the Best Manufacturing Practices Center of Excellence (BMPCOE) in College Park, Maryland, supports several communication features. These features include the Program Manager's WorkStation (**PMWS**), electronic mail and file transfer capabilities, as well as access to Special Interest Groups (SIGs) for specific topic information and communication. The BMPnet can be accessed through the World Wide Web (at http://www.bmpcoe.org), through free software that connects directly over the Internet or through a modem. The PMWS software is also available on CD-ROM.



PMWS provides users with timely acquisition and engineering information through a series of interrelated software environments and knowledge-based packages. The main components of PMWS are KnowHow, SpecRite, the Technical Risk Identification and Mitigation System (TRIMS), and the BMP Database.

KnowHow is an intelligent, automated program that provides rapid access to information through an intelligent search capability. Information currently available in KnowHow handbooks includes Acquisition Streamlining, Non-Development Items, Value Engineering, NAVSO P-6071 (Best Practices Manual), MIL-STD-2167/2168 and the DoD 5000 series documents. KnowHow cuts document search time by 95%, providing critical, user-specific information in under three minutes.

SpecRite is a performance specification generator based on expert knowledge from all uniformed services. This program guides acquisition personnel in creating specifications for their requirements, and is structured for the build/approval process. SpecRite's knowledge-based guidance and assistance structure is modular, flexible, and provides output in MIL-STD 961D format in the form of editable WordPerfect® files.

TRIMS, based on DoD 4245.7-M (the transition templates), NAVSO P-6071, and DoD 5000 event-oriented acquisition, helps the user identify and rank a program's high-risk areas. By helping the user conduct a full range of risk assessments throughout the acquisition process, TRIMS highlights areas where corrective action can be initiated before risks develop into problems. It also helps users track key project documentation from concept through production including goals, responsible personnel, and next action dates for future activities.

The **BMP Database** contains proven best practices from industry, government, and the academic communities. These best practices are in the areas of design, test, production, facilities, management, and logistics. Each practice has been observed, verified, and documented by a team of government experts during BMP surveys.

Access to the BMPnet through dial-in or on Internet requires a special modem program. This program can be obtained by calling the BMPnet Help Desk at (301) 403-8179 or it can be downloaded from the World Wide Web at http://www.bmpcoe.org. To receive a user/e-mail account on the BMPnet, send a request to helpdesk@bmpcoe.org.

Appendix E

Best Manufacturing Practices Satellite Centers

There are currently ten Best Manufacturing Practices (BMP) satellite centers that provide representation for and awareness of the BMP program to regional industry, government and academic institutions. The centers also promote the use of BMP with regional Manufacturing Technology Centers. Regional manufacturers can take advantage of the BMP satellite centers to help resolve problems, as the centers host informative, one-day regional workshops that focus on specific technical issues.

Center representatives also conduct BMP lectures at regional colleges and universities; maintain lists of experts who are potential survey team members; provide team member training; and train regional personnel in the use of BMP resources such as the BMPnet.

The ten BMP satellite centers include:

<u>**California**</u>

Chris Matzke
BMP Satellite Center Manager
Naval Warfare Assessment Division
Code QA-21, P.O. Box 5000
Corona, CA 91718-5000
(909) 273-4992
FAX: (909) 273-4123
cmatzke@bmpcoe.org

Jack Tamargo
BMP Satellite Center Manager
257 Cottonwood Drive
Vallejo, CA 94591
(707) 642-4267
FAX: (707) 642-4267
jtamargo@bmpcoe.org

<u>**District of Columbia**</u>

Chris Weller
BMP Satellite Center Manager
U.S. Department of Commerce
14th Street & Constitution Avenue, NW
Room 3876 BXA
Washington, DC 20230
(202) 482-8236/3795
FAX: (202) 482-5650
cweller@bxa.doc.gov

<u>**Illinois**</u>

Thomas Clark
BMP Satellite Center Manager
Rock Valley College
3301 North Mulford Road
Rockford, IL 61114
(815) 654-5515
FAX: (815) 654-4459
adme3tc@rvcux1.rvc.cc.il.us

<u>**Iowa**</u>

Bruce Coney
Program Manager
Iowa Procurement Outreach Center
200 East Grand Avenue
Des Moines, IA 50309
(515) 242-4888
FAX: (515) 242-4893
bruce.coney@ided.state.ia.us

<u>**Louisiana**</u>

Al Knecht
Director
Maritime Environmental Resources & Information Center
Gulf Coast Region Maritime Technology Center
University of New Orleans
810 Engineering Building
New Orleans, LA 70148
(504) 626-8918 / (504) 280-6271
FAX: (504) 727-4121
atk@neosoft.com

<u>**Michigan**</u>

Maureen H. Reilly
SAE/BMP Satellite Center Manager
755 W. Big Beaver Road, Suite 1600
Troy, MI 48084
(724) 772-8564
FAX: (724) 776-0243
reilly@sae.org

Roy T. Trent
SAE/BMP Automotive Manufacturing Initiative Manager
755 W. Big Beaver Road, Suite 1600
Troy, MI 48084
(248) 273-2455
FAX: (248) 273-2494
bounder@ees.eesc.com

Ohio

Karen Malone
BMP Satellite Center Manager
Edison Welding Institiute
1250 Arthur E. Adams Drive
Columbus, Ohio 43221-3585
(614) 688-5111
FAX: (614) 688-5001
karen_malone@ewi.org

Pennsylvania

Sherrie Snyder
BMP Satellite Center Manager
MANTEC, Inc.
P.O. Box 5046
York, PA 17405
(717) 843-5054, ext. 225
FAX: (717) 854-0087
snyderss@mantec.org

Tennessee

Tammy Graham
BMP Satellite Center Manager
Lockheed Martin Energy Systems
P.O. Box 2009, Bldg. 9737
M/S 8091
Oak Ridge, TN 37831-8091
(423) 576-5532
FAX: (423) 574-2000
tgraham@bmpcoe.org

Appendix F
Navy Manufacturing Technology Centers of Excellence

The Navy Manufacturing Sciences and Technology Program established the following Centers of Excellence (COEs) to provide focal points for the development and technology transfer of new manufacturing processes and equipment in a cooperative environment with industry, academia, and Navy centers and laboratories. These COEs are consortium-structured for industry, academia, and government involvement in developing and implementing technologies. Each COE has a designated point of contact listed below with the individual COE information.

Best Manufacturing Practices Center of Excellence

The Best Manufacturing Practices Center of Excellence (BMPCOE) provides a national resource to identify and promote exemplary manufacturing and business practices and to disseminate this information to the U.S. Industrial Base. The BMPCOE was established by the Navy's BMP program, Department of Commerce's National Institute of Standards and Technology, and the University of Maryland at College Park, Maryland. The BMPCOE improves the use of existing technology, promotes the introduction of improved technologies, and provides non-competitive means to address common problems, and has become a significant factor in countering foreign competition.

Point of Contact:
Mr. Ernie Renner
Best Manufacturing Practices Center of Excellence
4321 Hartwick Road
Suite 400
College Park, MD 20740
(301) 403-8100
FAX: (301) 403-8180
ernie@bmpcoe.org

Center of Excellence for Composites Manufacturing Technology

The Center of Excellence for Composites Manufacturing Technology (CECMT) provides a national resource for the development and dissemination of composites manufacturing technology to defense contractors and subcontractors. The CECMT is managed by the Great Lakes Composites Consortium and represents a collaborative effort among industry, academia, and government to develop, evaluate, demonstrate, and test composites manufacturing technologies. The technical work is problem-driven to reflect current and future Navy needs in the composites industrial community.

Point of Contact:
Mr. James Ray
Center of Excellence for Composites Manufacturing Technology
c/o GLCC, Inc.
103 Trade Zone Drive
Suite 26C
West Columbia, SC 29170
(803) 822-3708
FAX: (803) 822-3710
jrglcc@glcc.org

Electronics Manufacturing Productivity Facility

The Electronics Manufacturing Productivity Facility (EMPF) identifies, develops, and transfers innovative electronics manufacturing processes to domestic firms in support of the manufacture of affordable military systems. The EMPF operates as a consortium comprised of industry, university, and government participants, led by the American Competitiveness Institute under a CRADA with the Navy.

Point of Contact:
Mr. Alan Criswell
Electronics Manufacturing Productivity Facility
One International Plaza
Suite 600
Philadelphia, PA 19113
(610) 362-1200
FAX: (610) 362-1290
criswell@aci-corp.org

National Center for Excellence in Metalworking Technology

The National Center for Excellence in Metalworking Technology (NCEMT) provides a national center for the development, dissemination, and implementation of advanced technologies for metalworking products and processes. The NCEMT, operated by Concurrent Technologies Corporation, helps the

Navy and defense contractors improve manufacturing productivity and part reliability through development, deployment, training, and education for advanced metalworking technologies.

Point of Contact:
Mr. Richard Henry
National Center for Excellence in Metalworking Technology
c/o Concurrent Technologies Corporation
100 CTC Drive
Johnstown, PA 15904-3374
(814) 269-2532
FAX: (814) 269-2501
henry@ctc.com

Navy Joining Center

The Navy Joining Center (NJC) is operated by the Edison Welding Institute and provides a national resource for the development of materials joining expertise and the deployment of emerging manufacturing technologies to Navy contractors, subcontractors, and other activities. The NJC works with the Navy to determine and evaluate joining technology requirements and conduct technology development and deployment projects to address these issues.

Point of Contact:
Mr. David P. Edmonds
Navy Joining Center
1250 Arthur E. Adams Drive
Columbus, OH 43221-3585
(614) 688-5096
FAX: (614) 688-5001
dave_edmonds@ewi.org

Energetics Manufacturing Technology Center

The Energetics Manufacturing Technology Center (EMTC) addresses unique manufacturing processes and problems of the energetics industrial base to ensure the availability of affordable, quality, and safe energetics. The focus of the EMTC is on process technology with a goal of reducing manufacturing costs while improving product quality and reliability. The EMTC also maintains a goal of development and implementation of environmentally benign energetics manufacturing processes.

Point of Contact:
Mr. John Brough
Energetics Manufacturing Technology Center
Indian Head Division
Naval Surface Warfare Center
101 Strauss Avenue
Building D326, Room 227
Indian Head, MD 20640-5035
(301) 744-4417
DSN: 354-4417
FAX: (301) 744-4187
mt@command.ih.navy.mil

Institute for Manufacturing and Sustainment Technologies

The Institute for Manufacturing and Sustainment Technologies (iMAST), was formerly known as Manufacturing Science and Advanced Materials Processing Institute. Located at the Pennsylvania State University's Applied Research Labortory, the primary objective of iMAST is to address challenges relative to Navy and Marine Corps weapon system platforms in the areas of mechnical drive transmission techologies, materials science technologies, high energy processing technologies, and repair technology.

Point of Contact:
Mr. Henry Watson
Institute for Manufacturing and Sustainment Technologies
ARL Penn State
P.O. Box 30
State College, PA 16804-0030
(814) 865-6345
FAX: (814) 863-1183
hew2@psu.edu

National Network for Electro-Optics Manufacturing Technology

The National Netowork for Electro-Optics Manufacturing Technology (NNEOMT), a low overhead virtual organization, is a national consortium of electro-optics industrial companies, universities, and government research centers that share their electro-optics expertise and capabilities through project teams focused on Navy requirements. NNEOMT is managed by the Ben Franklin Technology Center of Western Pennsylvania.

Point of Contact:
Dr. Raymond V. Wick
National Network for Electro-Optics Manufacturing Technology
One Parks Bend
Box 24, Suite 206
Vandergrift, PA 15690
(724) 845-1138
FAX: (724) 845-2448
wick@nneomt.org

Gulf Coast Region Maritime Technology Center

The Gulf Coast Region Maritime Technology Center (GCRMTC) is located at the University of New Orleans and focuses primarily on product developments in support of the U.S. shipbuilding industry. A sister site at Lamar University in Orange, Texas focuses on process improvements.

Point of Contact:
Dr. John Crisp, P.E.
Gulf Coast Region Maritime Technology Center
University of New Orleans
College of Engineering
Room EN-212
New Orleans, LA 70148
(504) 280-5586
FAX: (504) 280-3898
jncme@uno.edu

Manufacturing Technology Transfer Center

The focus of the Manufacturing Technology Transfer Center (MTTC) is to implement and integrate defense and commercial technologies and develop a technical assistance network to support the Dual Use Applications Program. MTTC is operated by Innovative Productivity, Inc., in partnership with industry, government, and academia.

Point of Contact:
Mr. Raymond Zavada
Manufacturing Technology Transfer Center
119 Rochester Drive
Louisville, KY 40214-2684
(502) 452-1131
FAX: (502) 451-9665
rzavada@mttc.org

Appendix G
Completed Surveys

As of this publication, 114 surveys have been conducted and published by BMP at the companies listed below. Copies of older survey reports may be obtained through DTIC or by accessing the BMPnet. Requests for copies of recent survey reports or inquiries regarding the BMPnet may be directed to:

Best Manufacturing Practices Program
4321 Hartwick Rd., Suite 400
College Park, MD 20740
Attn: Mr. Ernie Renner, Director
Telephone: 1-800-789-4267
FAX: (301) 403-8180
ernie@bmpcoe.org

1985	Litton Guidance & Control Systems Division - Woodland Hills, CA
1986	Honeywell, Incorporated Undersea Systems Division - Hopkins, MN (Alliant TechSystems, Inc.) Texas Instruments Defense Systems & Electronics Group - Lewisville, TX General Dynamics Pomona Division - Pomona, CA Harris Corporation Government Support Systems Division - Syosset, NY IBM Corporation Federal Systems Division - Owego, NY Control Data Corporation Government Systems Division - Minneapolis, MN
1987	Hughes Aircraft Company Radar Systems Group - Los Angeles, CA ITT Avionics Division - Clifton, NJ Rockwell International Corporation Collins Defense Communications - Cedar Rapids, IA UNISYS Computer Systems Division - St. Paul, MN (Paramax)
1988	Motorola Government Electronics Group - Scottsdale, AZ General Dynamics Fort Worth Division - Fort Worth, TX Texas Instruments Defense Systems & Electronics Group - Dallas, TX Hughes Aircraft Company Missile Systems Group - Tucson, AZ Bell Helicopter Textron, Inc. - Fort Worth, TX Litton Data Systems Division - Van Nuys, CA GTE C^3 Systems Sector - Needham Heights, MA
1989	McDonnell-Douglas Corporation McDonnell Aircraft Company - St. Louis, MO Northrop Corporation Aircraft Division - Hawthorne, CA Litton Applied Technology Division - San Jose, CA Litton Amecom Division - College Park, MD Standard Industries - LaMirada, CA Engineered Circuit Research, Incorporated - Milpitas, CA Teledyne Industries Incorporated Electronics Division - Newbury Park, CA Lockheed Aeronautical Systems Company - Marietta, GA Lockheed Corporation Missile Systems Division - Sunnyvale, CA Westinghouse Electronic Systems Group - Baltimore, MD General Electric Naval & Drive Turbine Systems - Fitchburg, MA Rockwell International Corporation Autonetics Electronics Systems - Anaheim, CA TRICOR Systems, Incorporated - Elgin, IL
1990	Hughes Aircraft Company Ground Systems Group - Fullerton, CA TRW Military Electronics and Avionics Division - San Diego, CA MechTronics of Arizona, Inc. - Phoenix, AZ Boeing Aerospace & Electronics - Corinth, TX Technology Matrix Consortium - Traverse City, MI Textron Lycoming - Stratford, CT

1991	*Resurvey of Litton Guidance & Control Systems Division* - Woodland Hills, CA Norden Systems, Inc. - Norwalk, CT Naval Avionics Center - Indianapolis, IN United Electric Controls - Watertown, MA Kurt Manufacturing Co. - Minneapolis, MN MagneTek Defense Systems - Anaheim, CA Raytheon Missile Systems Division - Andover, MA AT&T Federal Systems Advanced Technologies and AT&T Bell Laboratories - Greensboro, NC and Whippany, NJ *Resurvey of Texas Instruments Defense Systems & Electronics Group* - Lewisville, TX
1992	Tandem Computers - Cupertino, CA Charleston Naval Shipyard - Charleston, SC Conax Florida Corporation - St. Petersburg, FL Texas Instruments Semiconductor Group Military Products - Midland, TX Hewlett-Packard Palo Alto Fabrication Center - Palo Alto, CA Watervliet U.S. Army Arsenal - Watervliet, NY Digital Equipment Company Enclosures Business - Westfield, MA and Maynard, MA Computing Devices International - Minneapolis, MN *(Resurvey of Control Data Corporation Government Systems Division)* Naval Aviation Depot Naval Air Station - Pensacola, FL
1993	NASA Marshall Space Flight Center - Huntsville, AL Naval Aviation Depot Naval Air Station - Jacksonville, FL Department of Energy Oak Ridge Facilities (Operated by Martin Marietta Energy Systems, Inc.) - Oak Ridge, TN McDonnell Douglas Aerospace - Huntington Beach, CA Crane Division Naval Surface Warfare Center - Crane, IN and Louisville, KY Philadelphia Naval Shipyard - Philadelphia, PA R. J. Reynolds Tobacco Company - Winston-Salem, NC Crystal Gateway Marriott Hotel - Arlington, VA Hamilton Standard Electronic Manufacturing Facility - Farmington, CT Alpha Industries, Inc. - Methuen, MA
1994	Harris Semiconductor - Melbourne, FL United Defense, L.P. Ground Systems Division - San Jose, CA Naval Undersea Warfare Center Division Keyport - Keyport, WA Mason & Hanger - Silas Mason Co., Inc. - Middletown, IA Kaiser Electronics - San Jose, CA U.S. Army Combat Systems Test Activity - Aberdeen, MD Stafford County Public Schools - Stafford County, VA
1995	Sandia National Laboratories - Albuquerque, NM Rockwell Defense Electronics Collins Avionics & Communications Division - Cedar Rapids, IA *(Resurvey of Rockwell International Corporation Collins Defense Communications)* Lockheed Martin Electronics & Missiles - Orlando, FL McDonnell Douglas Aerospace (St. Louis) - St. Louis, MO *(Resurvey of McDonnell-Douglas Corporation McDonnell Aircraft Company)* Dayton Parts, Inc. - Harrisburg, PA Wainwright Industries - St. Peters, MO Lockheed Martin Tactical Aircraft Systems - Fort Worth, TX *(Resurvey of General Dynamics Fort Worth Division)* Lockheed Martin Government Electronic Systems - Moorestown, NJ Sacramento Manufacturing and Services Division - Sacramento, CA JLG Industries, Inc. - McConnellsburg, PA
1996	City of Chattanooga - Chattanooga, TN Mason & Hanger Corporation - Pantex Plant - Amarillo, TX Nascote Industries, Inc. - Nashville, IL Weirton Steel Corporation - Weirton, WV NASA Kennedy Space Center - Cape Canaveral, FL Department of Energy, Oak Ridge Operations - Oak Ridge, TN

1997	Headquarters, U.S. Army Industrial Operations Command - Rock Island, IL SAE International and Performance Review Institute - Warrendale, PA Polaroid Corporation - Waltham, MA Cincinnati Milacron, Inc. - Cincinnati, OH Lawrence Livermore National Laboratory - Livermore, CA Sharretts Plating Company, Inc. - Emigsville, PA Thermacore, Inc. - Lancaster, PA Rock Island Arsenal - Rock Island, IL Northrop Grumman Corporation - El Segundo, CA *(Resurvey of Northrop Corporation Aircraft Division)* Letterkenny Army Depot - Chambersburg, PA Elizabethtown College - Elizabethtown, PA Tooele Army Depot - Tooele, UT
1998	United Electric Controls - Watertown, MA Strite Industries Limited - Cambridge, Ontario, Canada Northrop Grumman Corporation - El Segundo, CA Corpus Christi Army Depot - Corpus Christi, TX Anniston Army Depot - Anniston, AL Naval Air Warfare Center, Lakehurst - Lakehurst, NJ Sierra Army Depot - Herlong, CA ITT Industries Aerospace/Communications Division - Fort Wayne, IN Raytheon Missile Systems Company - Tucson, AZ Naval Aviation Depot North Island - San Diego, CA *U.S.S. Carl Vinson* (CVN-70) - Commander Naval Air Force, U.S. Pacific Fleet Tobyhanna Army Depot - Tobyhanna, PA
1999	Wilton Armetale - Mount Joy, PA Applied Research Laboratory, Pennsylvania State University - State College, PA

INTERNET DOCUMENT INFORMATION FORM

A . Report Title: Best Manufacturing Practices: Report of Survey Conducted at Applied Research Laboratory, Pennsylvania State University, State College, PA

B. DATE Report Downloaded From the Internet: 12/11/01

C. Report's Point of Contact: (Name, Organization, Address, Office Symbol, & Ph #): **Best Manufacturing Practices**
Center of Excellence
College Park, MD

D. Currently Applicable Classification Level: Unclassified

E. Distribution Statement A: Approved for Public Release

F. The foregoing information was compiled and provided by:
DTIC-OCA, Initials: __VM__ Preparation Date 12/11/01

The foregoing information should exactly correspond to the Title, Report Number, and the Date on the accompanying report document. If there are mismatches, or other questions, contact the above OCA Representative for resolution.